Soil water repellency in Greenlandic soils: Effects of adding glacial rock flour.

*Master thesis*

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Preface

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Scientific paper: Glacial rock flour reduces the hydrophobicity of Greenlandic cultivated soils

Abstract

Soil water repellency (SWR) in soils is a property with significant consequences in the agricultural production and soil health. It is originated by the presence of hydrophobic organic compounds covering the soil surface. A total of 72 samples from Denmark (DK) and south of Greenland (GR-S) were analyzed, covering organic carbon (OC) contents between 0.01 and 0.46 kg kg$^{-1}$. The SWR was measured by the MED test across water contents in the SWR-w curve. Further the use of GRF, as soil amendment, to alleviate SWR was investigated. The aim of the study was: (1) Investigate SWR as function of water content in GR-S soils and compare them with DK soils, (2) Investigate the effect of GRF on water repellent GR-S soils, and (3) Determine if the soil water retention in GR-S soils can be applied to normalized SWR. As a result: (1) DK and GR-S soils are very strongly repellent, but DK soils have a bigger potential to develop strong hydrophobicity under dry conditions. OC is the main driver of repellency in both soils. (2) The mean reduction in the severity of SWR was significantly higher at 50, 300, and 500 t ha$^{-1}$ GRF relative to the control (p< 0.05), 75% of the Greenlandic soils reached hydrophilic conditions. (3) The normalization of SWR$\text{AREA}$ revealed the effect of GRF without the interaction of OC; significant reduction was observed with 500 t ha$^{-1}$ in soils with low OC and clay content.
List of abbreviations

SWR-w: Soil water repellency vs soil water content

SWR: soil water repellency

SWR_{AREA}: total degree of soil water repellency

WR: water repellency

WR_{60\degree C}: water repellency in soils after being oven dried at 60\degree C.

WR_{AD}: water repellency in soils after being air dried.

WR_{105\degree C}: water repellency in soils after being oven dried at 105\degree C.

WR_{MAX}: maximum SWR

w: soil water content or soil moisture.

w_{60}: water content of soils after being oven dried at 60\degree C.

w_{AD}: water content of soils after being air dried

w_{NON}: the critical soil-water content where the soil becomes hydrophilic

AD: air-dried

OC: organic carbon

MED: molarity of an ethanol droplet.

OM: organic matter

72.27 mN m^{-1}: surface tension of deionized water

GR-S: South Greenlandic soils

DK: Danish peat soils

WSIs: water vapor sorption isotherms
1 INTRODUCTION

Water repellency in soils is caused by hydrophobic coatings present in certain vegetation types, plant roots, plant leaves, decomposing litter, fungal, and soil microorganisms. It is mainly controlled by organic carbon, temperature, soil texture, soil moisture, etc., (de Jonge et al., 1999; Doerr et al., 2000; Knadel et al., 2016; Wijewardana et al., 2016).

Over the recent decades, the springtime snow cover has decreased in the Arctic region and forecast climate change would increase the temperature in autumn and winter, leading to a continuous decrease of snow cover. In turn, the growing season will expand the duration of the growing season by two months in the south of Greenland, opening new land and improving preconditions for agricultural production (Box et al., 2019; Caviezel et al., 2017; Zhou et al., 2018). Nevertheless, nowadays agricultural production in Greenland is not self-sufficient yet, even with the increasing use of fertilizer in the past few years, yields production has been negatively affected by dry summers (Høegh Bojesen & Olsen, 2019).

South Greenlandic soils are characterized by coarse texture, medium to high non-degraded organic matter, poor soil structure development, poor aeration, low amount of nutrients, and severe water repellent soils during dry periods (Høegh Bojesen & Olsen, 2019; Pesch et al., 2020). Therefore, according to Caviezel et al., (2017), the raise in temperature and the length of the growing season, does not necessarily increase the potential for land use intensification and expansion due to the low nutrient levels and unsuitable soil texture in Greenlandic soils. On the other hand, climate change with longer dry periods could enhance the potential water repellency and it would put in risk yield production. Hence, the agricultural sector must adapt to current and future changes to produce higher levels of local yield production (Høegh Bojesen & Olsen, 2019).

Glacial rock flour (GRF) has been studied in the last few years as a potential soil fertilizer (Pesch et al., 2022). It consists of very fine-grained silt with a median size of < 10 μm and it is formed when glaciers crush underlying rocks and stones. GRF is found around Greenland as terrestrial deposits (Bennike et al., 2019; Høegh Bojesen and Olsen, 2019; Amino et al., 2021).

The possible improvement of nutrient-poor soils by applying GRF as a soil amendment has been suggested, since it has high pH (~8), contains an extensive range of minerals and a wide
spectrum of trace elements such as Ca, K, Mg, small amounts of P and S, and no nitrogen (N). Thus, rock flour can neutralize acidity, delay soil depletion, restore nutrient-poor soils, and supply nutrients to plants. Further, it can develop soil structure and increase its water holding capacity (Bennike et al., 2019; Gunnarsen et al., 2019; Høegh Bojesen & Olsen, 2019).

An increase in yield production with the addition of GRF in soils from south of Greenlandic has been reported by Gunnarsen et al., (2019) and Sukstorf et al., (2020). The letter combined GRF with artificial N-P-K fertilizer. Further, the plant available water increased with the addition of 5% GRF to a sandy soil in a study conducted by Pesch et al., (2022). Hence, the GRF is a potential climate-positive natural soil amendment that could alleviate the degree of water repellency in south Greenlandic soils.

1.1 Project Aim

The project aims to determine the degree of water repellency in South Greenlandic soils as compared to soils from Denmark. Additionally, the project seeks to determine the effects of the application of glacial rock flour (GRF) in different concentrations (50, 100, 300, and 500 t ha\(^{-1}\)) on soil water repellent soils from South Greenland.

1.2 Hypotheses

a) South Greenlandic soils are highly water repellent because of their high organic matter content. The degree of water repellency will be determined by the organic matter content.

b) The use of Glacial rock flour (GRF), as a soil amendment, will reduce the water repellency of South Greenlandic soils.

1.3 Specific Objectives

a) Investigate soil water repellency (SWR) as a function of water content in South Greenlandic soils and compare it to Danish peat soils.

b) Investigate the effect of Glacial rock flour (GRF), as a soil amendment, on the water repellency of Greenlandic soils.
c) Investigate if dry soil water retention in South Greenlandic soils can be applied to normalize SWR, such that small variations in texture and OC do not mask GRF effects on SWR.
2 LITERATURE REVIEW

2.1 Arctic soils characteristics

The Arctic region is the portion of the Northern Hemisphere located above the Arctic Circle. It covers approximately $7.2 \times 10^6$ km$^2$ of land area distributed among Canada and Russia with 66% of extension; and, the United States (Alaska), Denmark (Greenland), Norway, Iceland, Sweden, and Finland with smaller extents. Glaciers cover around 26% of this region, with 92% of glaciers placed in Greenland (ACIA, 2005; Margesin, 2009)

The Artic vegetation extends from the nearly continuous cover of shrub-tundra in the south, turning to a sparse cover of dwarf shrubs, herbs, mosses, and lichens in the north. Permafrost is defined as at least two consecutive years of frozen soil, frozen bedrock, and clear ice. It is constant in this region, reaching up to 100-500 m thickness in North America and >500m in Siberia. The active layer, the surface layer that freezes and thaws annually, is usually around 30-60cm thick, but it can reach up to 150-250 cm or more in the northern fringes. In early June snow-free sectors start thawing and are reaching their maximum in late July or early August (Margesin, 2009; Ping et al., 2015; Tedrow, 2005).

Geologically, the Arctic is characterized by significant areas of sedimentary igneous and metamorphic rocks. Greenland and the northeastern part of the Canadian Arctic are still covered by remains of glacial ice, and coastal areas are usually classified as marine deposits (derived from sea-level changes and glacial rebound). In contrast, eolian (loess), colluvial, and lacustrine origin surficial materials are extended over a large part of the Arctic in Eurasia and northwestern North America (Alaska and part of Yukon); and yedoma sediments (developed from colluvial materials) over the Siberian Arctic. Lastly, in the southern part of the Arctic, around 2-3m thick peat deposits are found, especially in lowlands and ice-wedge polygons (Margesin, 2009).

The arctic climate is characterized by short and cool summers, as well as long and extremely cold winters with temperatures from -10 to -40°C in the coldest period, and from 3 to 10°C in the warmest. However, in the northern extremities of the arctic region as Greenland, Svalbard, and Franz Josef Land the warmest temperatures are just about -1 and 0°C. In addition, the arctic region has low precipitation (60-160 mm) occurring mostly as snow. For
these reasons, the genesis of Artic soils is dominated by cryogenic processes, which drive the formation of permafrost-affected soils or commonly known as permafrost soils (Margesin, 2009; Tedrow, 2005).

Cryogenic processes are induced by the migration of unfrozen soil water towards the frozen front along the thermal gradient, i.e., from warm to cold in the frozen system (Hartemink, 2006; Margesin, 2009). Such processes are:

– **Freeze-thaw**: Thaw of active surface layer every summer. It is driven by soil temperature (ST), which influences soil water movement, material, and energy transfer in the soil surface and downwards into the deeper soil layers as the frozen soil (Figure 1) (Bo et al., 2021; FAO, 2006; Qin et al., 2021).

– **Cryoturbation (frost churning)**: It is the deformation of soil horizons produced by freeze-thaw processes. As a result, in the soil profile, the topsoil material moves towards deeper soil layers (within the active layer) leading to the translocation of organic matter and carbon storage (Figure 2), and from deeper soil, minerals and nutrients are transported to the surface (van Huissteden, 2020).

– **Frost heave**: Accumulation of excess ground ice in permafrost soil, leading to the development of its soil surface, which moves vertically downwards or upwards when the soil is freezing or frozen. Subsequently, ice lenses or layers are formed (Figure 3), which in turn displays segregation ice. The bulk of the soil ice content known as frost heave is often made up of segregation ice (van Huissteden, 2020).

– **Cryogenic sorting**: Patterned ground circles or small polygons, as a result of circulating soil movements driven by frost heave. These surface patterns are differentiated between sorted and non-sorted patterns. Sorted patterns are bordered by sorting of stones and finer-grained material (Figure 4a) as a result of the rising of the mineral material from a raw, in the form of a core. Non-sorted patterns are delineated by vegetation or cracks (Figure 4b); these patterns are common all over the polar regions, principally in medium to clayed soil texture. On flat areas, sorted or non-sorted circles, as well as polygon nets, are typical. While on slopes, sorted or non-sorted stripes develop in a downslope direction (Tedrow, 2005; van Huissteden, 2020).
- **Ice build-up**: Accumulation of excess ice in the soil, as a result of ice segregation, forming ice lenses, and of the development of subsoil ice bodies (Figure 5) like ice-wedges and injection ice (van Huissteden, 2020).

- **Brunification**: It is the formation of brown-colored iron oxides which occurs as a consequence of weathering of silicates containing Fe (II), combined with decalcification and pH < 7. Thus, the C horizon is transformed into a Bw horizon. Brunification is associated with loamifination (formation of clay minerals) (Blume et al., 2015).

- **Thermal cracking**: It is characterized by a polygonal pattern of ice wedges. The crack forms in winter when soil cracks through cold periods, which are characterized by rapid air temperature drops between -25°C and -40°C and soil temperatures between -15°C and -25°C and a thin snow cover. This thermal contraction entails horizontal tensile stress on the soil.

  The crack is filled in with drifting snow or melt-water, which adds a vein of ice to the soil profile (Figure 7a, b). However, in dry environments with thin winter snow cover and ample eolian surface transport of sand, a wedge of vertically laminated sand is shaped. This repeatedly cracking process over years (Figure 7c), enhances the ice volume of permafrost (Figure 7d) (Blume et al., 2015; van Huissteden, 2020).

Besides the aforementioned processes others are involved in the formation of Arctic soils such as eluviation, gleying process (Figure 6), and salinization. Moreover, cryostatic desiccation (cryodesiccation) and thixotropy are not known as cryogenic processes; however, they influence the development of Arctic soils.

Cryodesiccation develops when the freezing front from the surface moves downwards and the front from the permafrost table moves upwards, and they meld during freeze-back (the freezing portion of the cycle). Consequently, the moisture between the two fronts is detached (frost desiccation). Cryoturbation along with desiccation causes granular structure in fined textured soils (Jones et al., 2005; Margesin, 2009)

Arctic soils with high silt content develop thixotropy phenomena in the thawed portion. Continuous stress or disturbance of these soils causes liquefaction, leading to semi-solid conditions or liquefied gel appearance (Figure 4c), which changes to a vesicular structure once the soil dries out (Jones et al., 2005; Zhang et al., 2017).
Figure 1. Conceptual model for the thawing and freezing process in the active layer of Russian Arctic soil (Ji et al., 2021).

Figure 2. Cryoturbated soil in the Yamal Peninsula, showing irregular, down-warped streaks of topsoil organic matter. Height of profile 0.7 m (van Huissteden, 2020).

Figure 3. Frost heave soil: ice lenses and a layer of nearly pure ice (Indigirka lowlands, Northeast Siberia) (van Huissteden, 2020).

Figure 4. Different pattern grounds in permafrost soils. (a) Non-sorted circles at a flat mountain top in northern Sweden; boundaries are lined with grasses with a thin snow cover. (b) Sorted circles, Spitsbergen, Kap Linné. (a) & (b) are result of cryogenic sorting processes (van Huissteden, 2020). (c) Thixotropic features in Histic Gleysol (Alekseev et al., 2017)
As a result of the interaction of cryogenic processes, arctic soils develop unique characteristics, both for their macromorphology and micromorphology, thermal characteristics; and physical, and chemical properties.

### 2.1.1 Macromorphology

According to Margesin (2009), Ping et al. (2015), & Tedrow (2005), the arctic soil surface is characterized by different patterned ground types as (1) sorting and (2) non-sorting circles as
shown in Figure 4a and b, which are the result of frost heave and sorting, and (3) unstable soil surface in Figure 4c, generated by thixotropic. At the beginning of the circle formation, the soil surface is lacking vegetation, but it starts growing and an organic horizon is formed. Nevertheless, this surface organic mat is disrupted by the annual differential heaving of the circle surface, leading to the formation of irregular surface organic horizons.

Ice-wedge polygon, one of the more common surfaces patterned ground, is displayed in Figure 7. It can vary between 5 and 50m diameter polygon units. As mentioned previously, frost heave produces changes of elevation of the soil surface, which may lead to a rise or reduction of the center of the ice-wedge polygon. Consequently, some parts of the polygon would be better drained, while other parts will develop into poorly drained areas; thus, ice-wedge controls surface water distribution and deforms developing soils. Salt crust appears in summer on soil surface because of high evapotranspiration rates, in the well-drained as well as xeric soils.

Figure 5 shows ice build-up in arctic soils. It increases the pore volume when soil is frozen, but when permafrost thaws, unfrozen pores cause settlement of soil surface and as a result, irregular topography known as thermokarst landscape or thermokarst lakes are formed.

Irregular or broken soil horizons as shown in Figure 2, along with involutions, organic intrusions, and organic matter accumulation, oriented rock fragments, silt enriched layers, and silt caps on top of the permafrost table, are typical in the subsoil as a result of cryoturbation. Differential frost heave transforms flat horizons into warped or wavy horizons, as well.

Soil horizons usually present granular, platy, blocky, wedge-shaped structures due to freeze-thaw processes and desiccation. In the active layer, fine-textured soil freezes above and below on two freezing fronts, where water migrates. Therefore, both freezing fronts become saturated with ice, prompting the formation of vertical cracks in the desiccated part of the active layer. Furthermore, cryodesiccation in fine-textured soils often leads to a massive structure plus a high bulk density value. Since the active nature of the permafrost, these macromorphological features can be found both in the active layer and/or in the near-surface permafrost. However, in poorly drained soils, water is enough to support layered cryostructure- ice, sediments, and rock- development all over the active layer.
In addition, soil horizon deformation is common in sloping areas together with sorted or non-sorted stripes developed in downslope direction, as a result of gravitational forces. Cryogenic sorting, annual freeze-thaw cycles, and solifluction – a slow flow of saturated soil downslope—are responsible for this phenomenon. Soil deformations develop into stripes or stone stripes. While the permafrost table acts as a moisture barrier, the soil develops gleying process together with greyish colors and redoximorphic features. It is particularly formed in loamy and fined-textured soils. However, in sandy soils located in the southern part of the Arctic, a thin eluvial or horizon E is formed through brunification.

2.1.2 Thermal characteristics

Soil temperatures are directly correlated to air temperature and reflect changing air temperatures, especially lower ones. However, as the buffering capacity of the active layer is limited, factors such as vegetation cover, soil moisture, the thickness of snow cover, and underlaying permafrost can alter this correlation. Therefore, a slight thermal gradient in the soil can be created, particularly in the high arctic (Margesin, 2009).

2.1.3 Physical properties

The deposition of the parent material dictates the texture of Arctic soils. Therefore, such soils have a varied range of textures, from coarse-textured to fine-textured soils. As mentioned before, the structure of the soil is the result of the cryogenic process. In that sense, desiccation and frost action; vein ice formation; and cryodesiccation during the freeze-back result in granular; platy, wedge-shaped, blocky; and massive structure, respectively. Since the water in permafrost soils migrates along the thermal gradient from warm to cold, the thickness of ice in the subsoil increases, as well as its volume over time (Margesin, 2009).

Moreover, as a result of the pattern ground formation process, soil types across the Arctic region can vary on a small or large scale, i.e., in ice-wedge polygons patterns; is common to find: (1) soils with a moderate amount of thick peat in the polygon trench, caused by massive ice; (2) soils on the borders with better drainage, as well as well-decomposed organic matter, developing an A horizon; (3) thick peats soils, in polygonal centers, across mineral sediment with various degrees of cryoturbation. On the other hand, in circle patterns moisture
availability, plant community distributions, and differential active layer dynamics are affected by a small-scale net of cracks (0.5-5m), developing different soil profile features across the circles (Ping et al., 2015)

### 2.1.4 Chemical properties

Similar to the soil texture, some chemical properties in Arctic soils depend on the parent material, such as pH. Through cryoturbation usually, the pH of the soil is similar to the parent material, due to the mixture and translocation of the fresh parent material to the near-surface and the soil material among the soil horizons. However, the land use can change pH value e.g., wet mineral soil in the tundra zone, have a pH range within 4.5-6.5, but it can switch to pH > 7 due to the dust of carbonate-bearing minerals, added to the soil from vegetation-free floodplains sources (Margesin, 2009; Tedrow, 2005).

Nitrogen, potassium, and phosphorus are enclosed into the soil surface organic matter, so the movement of solutes through the thermal gradient in Arctic soils results in the translocation of these nutrients, enriching the perennially frozen layer or frozen soil. For that reason, the content of these three nutrients in Arctic soils are usually low. Such a process occurs in both organic and mineral soils (Margesin, 2009).

Arctic soils are characterized by low electrical conductivity, except for soils developed on marine clays with 1.64–2.73 mmhos cm\(^{-1}\), and marine shale with 0.350–0.500 mmhos cm\(^{-1}\) (Margesin, 2009).

Regardless of the low biomass production in the permafrost-affected ecosystems in comparison to temperate ones, arctic soils sequester large amounts of organic carbon both in the active layer and the perennially frozen portion of the soil. Low decomposition rates, cryoturbation, and depositional environments have triggered soil carbon accumulation. i.e., Organic soils or peatlands have an average carbon content from 43 to 144 kg m\(^{-2}\), while in mineral soils the organic carbon ranges from 40 to 61 kg m\(^{-2}\) (Margesin, 2009; Ping et al., 2015).

Up to this time several classification systems for polar or arctic soils. However, Table 1 shows the four most used taxa nowadays.
### Table 1. Soil taxa used to describe Arctic soils

<table>
<thead>
<tr>
<th>Classification system</th>
<th>Soil taxa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil taxonomy</td>
<td>Gelisol (soil order)</td>
</tr>
<tr>
<td>World reference base (FAO)</td>
<td>Cryosol (soil unit)</td>
</tr>
<tr>
<td>Canadian</td>
<td>Cryosol (order)</td>
</tr>
<tr>
<td>Zonal system</td>
<td>Soils of the Cold Regions</td>
</tr>
</tbody>
</table>

*Source: elaborated from* (Tedrow, 2005)

2.2 Climate change in the Arctic region and opening for agricultural areas

The Arctic region has experienced significant changes as a consequence of climate change in the last 30-40 years, the most important are: (1) The mean annual temperature has increased by 2.7°C (3.1°C in the cold season and 1.8°C in the warm season). (2) The annual precipitation has raised 6.2% (6.8% in the cold season and 4.7% in the warm season). (3) Soil temperature has increased in the upper 10-20 m. It is reaching more than 2°C in the colder permafrost of the northern Arctic. (4) Elevated humidity at the Arctic surface. (5) Decrease of snowfall as an increase of rainfall in Greenland and regions with warmer winter; however, in the northern Arctic and lower elevations of Greenland the snowfall has increased. (6) Raise of the delivery of organic matter and nutrients in Arctic near-coastal zones, e.g., higher meltwater runoff of Greenlandic ice sheet is linked with higher sedimentation rates in the last century. (7) In the last 30-40 years the snow cover duration has reduced by two to four days per decade, and the snow extension on land has declined more than 30% during the Arctic spring (May-June). (8) Arctic ice decreased in extent, volume, and thickness. (9) Land ice loss, contributing 30% to the total sea-level rise since 1992 (Box et al., 2019).

All these changes have enhanced the thaw of permafrost, e.g., maximum thaw depths increased 1.6 cm yr⁻¹ between 1997 and 2010 in the North of Greenland (Box et al., 2019). Permafrost soils stand for approximately 24% of the landmass of the Arctic region and around 15% of the global landmass (Ping et al., 2015). The reduction of permafrost areas generates a decrease in soil strength and soil consolidation. As a result of thawed soil and reduction of excess ice, as well as the release of greenhouse gases into the atmosphere (Margesin, 2009). In addition, as a result of higher summer temperatures, the Arctic has become greener, e.g.,
from 1981 to 2011 the Normalized Difference Vegetation Index (NDVI) has raised 16.9% in Northern Alaska (Westegaard-Nielsen et al., 2015).

Snow is the main driver for ecosystem functioning in the Arctic region. Since the timing of snow is the key driver for the growing season period and the emission of CO$_2$ and CH$_4$; extended snow-free seasons will prolong the growing season, increasing CO$_2$ uptake and respiration in plants (Box et al., 2019).

Agriculture has developed rapidly in the last few years due to improvements in the infrastructure, which has led to the enhancement of the demand for agricultural products. Arctic agriculture involves cool-season forage crops, cool-season vegetables, small grains, livestock production, and reindeer herding. Nevertheless, production is limited by the cold climates, short growing seasons, and soil erosion in some areas. Therefore, a longer growing season (earlier beginning and a delayed ending) along with higher temperatures and ice-free periods on land surfaces, open the potential to larger agriculture production and land use expansion towards the north; thus, yield production is expected to increase (Box et al., 2019; Caviezel et al., 2017; Margesin, 2009; Westegaard-Nielsen et al., 2015; Zhou et al., 2018).

### 2.3 Subarctic soils and agriculture production

Greenland covers three climatic zones from north to south: high arctic, low arctic, and subarctic climate (Sørensen, 2020). Therefore, subarctic soils involve the south Greenlandic soils examined in this study.

The dominant soil types of South Greenland are (1) podzols, with glacial till, alluvial, or aeolian sand deposits as parent material; and (2) arctic brown soils, very coarse soil with weathering of the parent material. These soils are characterized by (1) Low amount of clay (2-10%) and higher contents of silt and sand, covering various textural classes as sand, loamy sandy, sandy loam, loam, and silty loam (Figure 8); (2) high contents of stone and gravel; (3) pH values ~5; (4) low nutrient content; (5) high non-degraded organic matter (OM) content (up to 324 kg kg$^{-1}$); (6) low dry bulk density (~1.10 g cm$^{-3}$), as result of high OM and freezing-thaw cycles; (7) poor soil structure development; (8) poor soil aeration; and, (9) water repellent soils. During dry periods 99% of the soil in southern Greenland is hydrophobic, as a result of high organic matter contents. As consequence, water repellent along with coarse-textured soils...
diminish soil moisture, affecting plant growth (Høegh Bojesen & Olsen, 2019; Pesch et al., 2020)

The biomass production in the last 30 years has increased 318 kg ha\(^{-1}\) in the Southwest and 108 kg ha\(^{-1}\) in South Greenland. According to Westergaard-Nielsen et al., (2015), biomass production will increase 50% by the end of the century, increasing twice the suitable areas for sheep farming (from 13600 ha to 27600 ha). Since agricultural fields are already located where mean temperatures are high (9.91°C), biomass expansion is controlled mainly by temperature fluctuations. However, soil nutrient levels and soil moisture, essential factors in agriculture production, were not considered in this study.

Over the recent decades, the springtime snow cover has decreased in the subarctic; climate change scenarios predict the increasing temperature in autumn and winter, which may lead to the continuous decrease of snow cover; and the current duration of the growing season will extend by approximately two months at the end of this century in the south of Greenland (Helama et al., 2011; Weber et al., 2020; Westergaard-Nielsen et al., 2015). In addition, the melting of the Greenlands Ice Sheet has experienced a 16% increase from 1979 to 2002, leaving some land to expand agriculture (ACIA, 2005). Therefore, the upcoming climate in Greenland is expected to improve the preconditions for agricultural production of winter fodder from the agricultural fields and grazing potential during summertime (Høegh Bojesen & Olsen, 2019; Lehmann et al., 2019; Sjursen et al., 2005; Westergaard-Nielsen et al., 2015).
Greenlandic agriculture involves sheep framing, winter fodder, and hay production. Nevertheless, in recent years crops like potatoes and turnips, and livestock production have grown commercially. Thus, the tillage of fodder fields and the application of industrial fertilizer have intensified agriculture production. Nowadays there are around 35-40 farmers in South Greenland; of 1100 ha of arable land 99 % is cultivated with grass for winter fodder and 1 % for growing potatoes. In addition, near 250 000 ha of permanent mountain pastures, are used for extensive grazing in the summer period (Bichet et al., 2013; Høegh Bojesen and Olsen, 2019; Lehmann et al., 2019).

Though the agriculture expansion in South Greenland in the last decades, it is not self-sufficient yet; around 40-50% of winter fodder was imported in 2007. To accomplish self-sufficiency, it is necessary to increase 55% of the current land or further increase the yield per area. The use of fertilizers has been enhanced since 1994, obtaining positive results in 2000, but since 2007 the intensification of dry summers has affected the soil moisture, negatively affecting the yield production (Caviezel et al., 2017).

Thus, the uncertainty of unpredictable weather and droughts, and the potential introduction of invasive species and pests as a result of rising temperatures, could affect agricultural activities in the South of Greenland. It must adapt to current and future changes to produce higher levels of local food production (Høegh Bojesen and Olsen, 2019).

2.4 Glacial Rock Flour (GRF)

Glacial rock flour (GRF) is formed when glaciers crush underlying rocks and stones. It consists of very fine-grained silt with a median size of < 10 µm. Then, GRF washes out from under the glacier, and it is deposited from the land to the coast of Greenland by dust deposition or meltwater (Figure 9). GRF can be found around Greenland as terrestrial deposits (Figure 10) or as marine deposits within the fjords near the outlets of the glacial rivers (Bennike et al., 2019; Høegh Bojesen and Olsen, 2019; Amino et al., 2021).
Several deposits of GRF have been found in the South Greenland, Tunulliarfik, and Igalikup Kangerlua sites; and, in West Greenland, the Lake Tasersuaq, which holds more than 50 m of fine-grained glacial rock flour (Bennike et al., 2019).

The possible improvement of nutrient-poor soils by applying GRF from Greenland has been investigated in the last years. A study conducted by Gunnarsen et al., (2019) showed an improvement in the growth of plants cultivated in soils with rock flour, as a result of the slow release of potassium (K) and magnesium (Mg). Since GRF has high pH (~8) and contains an extensive range of minerals and a wide spectrum of trace elements such as Ca, K, Mg, small amounts of P and S, and no nitrogen (N), rock flour can neutralize acidity, delay soil depletion, restore nutrient-poor soils and supply nutrients to plants. Further, it can develop soil structure and increase its water holding capacity (Bennike et al., 2019; Gunnarsen et al., 2019; Høegh Bojesen & Olsen, 2019).

2.5 Soil water repellency (SWR)

Water repellency or hydrophobicity in soils reduces the affinity of soils for water, i.e., rate of wetting and retention of water for seconds, hours, days, or weeks (Doerr et al., 2000).

Hydrophobic or hydrophilic solid surface behavior derives from mutual attractive forces between the solid surface and water (adhesion), and the attraction between the water molecules (cohesion). The adhesion is possible due to positive and negative ends of water, which are attracted by most natural surfaces that contain positively and negatively charged ions; however, the cohesion of water counters this attraction, acting as an opposite force.
Therefore, when cohesion forces are higher than adhesion forces, surface molecules of water will experience a net attractive force towards the interior, promoting the reduction of the surface area and is displaying a spherical shape like a droplet, i.e., hydrophobic behavior. To expand the surface area of water, surface tension or surface free energy of the solid must overpass the surface tension of water (72.75X10⁻³ N/m at 20°C), i.e., adhesive forces between soil and water exceed cohesion forces whiting the water. Thus, a solid with surface tension >72.75X10⁻³ N/m attracts water and is considered hydrophilic. The force of attraction rises with the increasing surface tension of the solid. As hydrophobic organic solids, originated from living or decomposing plants or microorganisms, have a surface tension <72.75X10⁻³ N/m, soils covered with these organic compounds have a reduced attraction towards the water and therefore are hydrophobic (Doerr et al., 2000; Hermansen, Moldrup, Müller, Knadel, et al., 2019; Knadel et al., 2016).

2.5.1 Factors controlling soil water repellency (SWR)

SWR is caused by hydrophobic organic compounds such as organic coatings and interstitial organic matter which contain fatty, humic, aliphatic acids, and plant debris. For example, strongly water repellent sandy soils are composed of less than 0.5% of hydrophobic organic coatings and moderately water repellent sandy soils are made up of 2-5% of hydrophobic organic matter (Doerr et al., 2000; Knadel et al., 2016).

The two compounds that induce water repellency in soils are aliphatic hydrocarbons and amphiphilic molecules, which are mainly long-chained fatty acids (Graber et al., 2009). Aliphatic hydrocarbons are non-polar, so almost water-insoluble; they consist of hydrogen and carbon with the carbon atoms set in an elongated chain. Amphiphilic molecules are polar substances of amphiphilic structure and consist of a hydrocarbon chain with one end hydrophilic and the second end hydrophobic. The hydrophilic end is made-up of a functional group with a positive and negative charge (Figure 11(I)). However, when the hydrophilic end covers the soil, the hydrophobic end is exposed to the solid surface (Figure 11(IIa)). Amphiphilic molecules are the principal component of hydrophobic coatings on water repellent sandy soils (Doerr et al., 2000). Sources of hydrophobic coatings are:
Figure 11. Amphiphilic molecule responsible for hydrophobicity in soils: (I) structure of hydrocarbon chain and its two ends; (II/a-c) alteration in the orientation of such molecules on a mineral surface while in contact with water (Doerr et al., 2000).

- **Vegetation:** (1) certain evergreen trees with a significant quantity of resins, waxes, or aromatic oils (fatty acids) as eucalyptus and pines; (2) shrubs, from temperate to semi-desert ecosystems; grassland and pasture, especially pasture grazed by animals; (3) some crops, e.g., blue lupin (*Lupinus consentinitii*) in Australia. This input into the soil can be either from decaying plant litter or root activity of plants (Doerr et al., 2000; Wijewardana et al., 2016).

- **Soil fungi and microorganisms:** fungal growth and soil microorganisms that induce water repellency are at the same time associated with specific vegetation. Some species cause hydrophobicity while others can reduce it. This process could happen at the same time since they participate in the decomposition of hydrophobic compounds. As a considerable number of algae and bacteria generate hydrophobic compounds, the input from microorganisms into soils is much higher than from vegetation (Doerr et al., 2000).

Water repellency in soils is controlled by:

- **Soil organic matter and humus:** there is a positive correlation between organic matter (OM) and/or organic carbon (OC) and water repellency in soils. However, this association only applies to a certain type of organic material since the degree of water repellency in soils is not proportional to the total amount of organic matter or carbon. Therefore, the quantity and quality of OM determine the degree of repellency. The organic material is mor-type (fluvic acid) humus, mull-type (humic acids), and litter (fatty acids) (Doerr et al., 2000).
− **Soil temperature and fire:** fire induces hydrophobicity and enlarges or reduces the hydrophobic surface in non-water repellent soils, since it enhances the bonding of hydrophobic compounds to soil particles, e.g., hydrophilic soil with 2-3% of organic matter exposed to head transforms it into hydrophobic. This effect depends on fire temperature, volume and type of little consumed, and the water content in the soil before the fire. Water repellency is enhanced in soils at temperatures of 175-200°C and above 280-300°C. hydrophobic compounds are destroyed. However, at lower temperatures, water repellency increases too if heating times are prolonged, e.g., oven-dried soil at 43°C or 70°C increases the degree of SWR (Doerr et al., 2000; Knadel et al., 2016)

− **Soil texture and clay content:** coarse-textured soils are more susceptible to water repellency due to their smaller surface area per unit volume in comparison with finer-textured soils, which can be covered by organic coatings. SWR can be found in soils with a high amount of clay, e.g., an extreme degree of repellency has been found in soils with 25%, 40%, or more clay content. Since the surface area of clay is reduced when it forms aggregates, allowing the cover of hydrophobic organic coatings on it (Doerr et al., 2000; Knadel et al., 2016).

− **Soil moisture:** Hydrophobic soils can absorb water, since water moves freely as vapour in these soils, leading to the redistribution of soil water, but it stops once the soil achieves its maximum absorption capacity for individual water molecules. Additionally, the amount of moisture is small in comparison with the amount of moisture that the soil can obtain from water in form of droplets, which process is restricted in hydrophobic soils (Doerr et al., 2000). Longer contact between water and soil surface may result in the reorganization of amphiphilic molecules as is shown in Figure 11(II, a-c), resulting in destabilization of repellency and leading to wettable soil. The polar groups interact with water molecules when soil is wet, but when the soil is dry these polar groups interact with each other or with the soil surface. Therefore, water repellency is less severe during wet periods and restored during dry periods. For that reason, SWR is thought of as a seasonal phenomenon. However, hydrophobic soils have been found in soils Great Britain, the Netherlands, Sweden, and Denmark under a considerable amount of soil moisture. Further, water repellency increases with increasing water content between air dry and
wilting point, thus water repellency is not restricted to dry climates or dry season (de Jonge et al., 1999; Doerr et al., 2000; Knadel et al., 2016; Wijewardana et al., 2016).

The degree of SWR is influenced by pH, land use, and management as well (Hermansen, Moldrup, Müller, Jensen, et al., 2019). Figure 12 displays a summary of the sources of hydrophobic coatings and the main factors influencing water repellency in soils.

Figure 12. Diagram of the sources of organic hydrophobic coatings in soils and how soil properties control water repellency (Ruthrof et al., 2019).
2.5.2 The severity of water repellency and its classification

Hydrophobicity in soils can be determined by several methods, but the most used are water drop penetration time (WDPT) and molarity of an ethanol droplet (MED), also called percentage ethanol or critical surface tension test. WDPT determines the persistence of SWR, measuring how long it takes for a drop of water to be absorbed or infiltrated on the soil surface, while the MED determines the severity of SWR; in other words, how strong the water is repelled by soil, measuring the drop water contact angles. It only measures water-repellent soils with contact angles greater than 90°; contact angles >0° to 90°, known as subcritical SWR, are measured by the sessile drop method (SDM) (Chau et al., 2014; Doerr et al., 2000; Wijewardana et al., 2016). Soils with subcritical SWR present lesser extend changes to hydrological processes; thus, it is often disregarded and considered hydrophilic (Chau et al., 2014)

The MED test uses ethanol and deionized water solutions. Different concentrations of ethanol are used to reduce the surface tension of deionized water (72.2 mN m⁻¹) at 20°C. Thus, the higher concentration of ethanol employed to render hydrophobic soils into hydrophilic the higher the severity of SWR. The maximum ethanol concentration (%) completely infiltrated after 5s is the severity of SWR (de Jonge et al., 1999; Hermansen, Moldrup, Müller, Jensen, et al., 2019; Knadel et al., 2016)

In contrast to Doerr (1998) and King (1981), who used 3 and 10s as infiltration times, in this study the infiltration time used was 5s. WATSON CL & LETEY J, (1970) evaluated the relationship between liquid-solid contact angle and surface tension using ethanol solution concentrations. They found that the infiltration time of 5s is equivalent to a contact angle of 90° (Hermansen, 2019).

The classification of the severity of water repellency in soils has been developed using 3 and 10s as infiltration times by Doerr (1998) and King (1981) respectively. Therefore, there is not a classification for the MED test using 5s as infiltration time, which is used in this study. Table 2 presents the severity and persistence categories of water repellency in air-dried soils at 20°C. Table 2 was used to compare the results of this study to previous studies which used a different methodology.
Table 2. Classification of soil water repellency in air-dried soils at 20°C: WDPT (Bisdom et al., 1993), MED 1 (Doerr, 1998) and MED 2 (King, 1981).

<table>
<thead>
<tr>
<th>Time</th>
<th>Persistence</th>
<th>% Ethanol</th>
<th>Severity</th>
<th>% Ethanol</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5 s</td>
<td>Wettable</td>
<td>1</td>
<td>Very hydrophilic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 s</td>
<td>Slightly water repellent</td>
<td>3</td>
<td>Hydrophilic</td>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>600 s</td>
<td>Strongly water repellent</td>
<td>5</td>
<td>Slightly hydrophobic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3600 s</td>
<td>Severely water repellent</td>
<td>8.5</td>
<td>Moderately hydrophobic</td>
<td>2.2</td>
<td>Moderate</td>
</tr>
<tr>
<td>&gt; 3600 s</td>
<td>Extremely water repellent</td>
<td>13</td>
<td>Strongly hydrophobic</td>
<td>3</td>
<td>Severe</td>
</tr>
<tr>
<td>1-3 h</td>
<td>Extremely water repellent</td>
<td>24</td>
<td>Very strongly hydrophobic</td>
<td>&gt;3</td>
<td>Very severe</td>
</tr>
<tr>
<td>3-6 h</td>
<td>Extremely water repellent</td>
<td>36</td>
<td>Extremely hydrophobic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;6 h</td>
<td>Extremely water repellent</td>
<td>&gt;36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: elaborated from (Doerr, 1998; King, 1981). The infiltration time used in each MED test is shown in brackets.

2.5.3 Soil water repellency vs water content (SWR-w) curve

The relationship between the degree of SWR and the water content, either volumetric or gravimetric, is termed as soil water repellency-water content (SWR-w) curve (Hermansen, Moldrup, Müller, Jensen, et al., 2019) or soil water repellency characteristic curve (SWRCC) (Wijewardana et al., 2016).

Figure 13 shows SWR-w curve functional parameters. Water repellency (WR) (mN m⁻¹) is measured at several points across the w (kg kg⁻¹) range where the soil is hydrophobic, from dry to wet conditions; i.e., beginning at WR after pretreatment at 105°C (WR₁₀⁵°C), 60°C (WR₆₀⁰°C), air-dried (WRₐₐ₅), all considered as potential repellency; following with water-repellency between AD and the critical soil water content (wₐ₉₉), where the maximum WR is reached (WR₉₉₉). W₉₉₉ is the water content where WR is no longer present, i.e., the soil becomes completely hydrophilic. For each WR measurement the w is recorded, e.g., w₆₀°C, wₐ₅, w₉₉₉. The total severity of soil water repellency is calculated as the integrated trapezoidal area underneath of the curve, SWRAREA (mN m⁻¹ kg kg⁻¹) (Doerr et al., 2000; Hermansen, Moldrup, Müller, Jensen, et al., 2019; Leelamanie & Karube, 2010a).

As mentioned before, the MED test measures the severity of SWR using different concentrations of ethanol in percentage. Such is converted into surface tension, millinewton per meter (mN m⁻¹), and expressed in the y axis in Figure 13. Notice that the closer surface tension of the soil to the water (72.2 mN m⁻¹), the less severe water-repellent it is.
Figure 13. Measured soil water repellency (SWR) vs soil water content (w) curve. The SWR-w curve is characterized by (1) water repellency and w values at standardized pretreatment after the soil is dried at 105°C, 60°C, and AD (air-dried) conditions; (2) $W_{NON}$, the critical soil-water content where the soil becomes hydrophilic; (3) $WR_{MAX}$ represents the maximum SWR at specific water content in the w interval from AD to $W_{NON}$; (4) $SWR_{AREA}$ is the total degree of soil water repellency calculated as the integrated trapezoidal area underneath of SWR-w curve (Hermansen, Moldrup, Müller, Jensen, et al., 2019).

The severity of SWR and w is a non-linear relationship, thus the shape of the SWR-w curve differs between soils. Three different types of SWR-w curves described by de Jonge et al., (1999) are presented in Figure 14. In the flat curve, the soil is completely hydrophilic. In the single-peak or unimodal curve, the severity of WR increases from dry conditions, it reaches a maximum point $WR_{MAX}$, and decreases until the critical water content $W_{NON}$. For the double-peak curve or bimodal curve, it starts with the first peak in the dry conditions, then it decreases and/or reaches hydrophilic conditions; afterward, the second peak starts and follows the same display of the unimodal curve (de Jonge et al., 1999; Hermansen, Moldrup, Müller, Jensen, et al., 2019)
2.5.4 Effects of SWR on ecosystem and agriculture systems

Water repellency is not restricted to a specific soil type, organic carbon content level, texture class, and mineralogical origin. As well, SWR has been documented in a range of climates from tropical to sub-arctic; in all continents, but Antarctica; in different vegetation types and land uses, i.e., grasslands, forest, agricultural land, and even mining sites (Chau et al., 2014; Jordán et al., 2013). Therefore, SWR effects are widespread too.

SWR affects significantly plant growth due to the reduction of infiltration capacity of soils, stimulates and accelerates soil erosion by water and wind, fostering rain splash detachment, promoting overland flow. In addition, SWR produces uneven wetting patterns, affects plant nutrition and water availability, reduces soil fertility, develops preferential flow, accelerates the leaching of agrochemicals and/or nutrients, thus the filtering capacity of soils for nutrients and chemicals is hampered, leading to the increase of contamination risk (Doerr et al., 2000; Hermansen, Moldrup, Müller, Jensen, et al., 2019; Jordán et al., 2013).

The consequences of water repellency in soils generate an important loss in the agricultural production since soils repel rainfall or irrigation water, which causes problems in plant
growth, e.g., the pasture production in New Zealand is affected by 30-40% by water repellency, leading to the loss of €245 per ha. Since the 75% of the agricultural land is under pasture, these effects have an important impact on the agricultural sector (Deurer et al., 2011). In Australia more than 10 Mha of sandy soils have been identified as water repellent, limiting crop production.

2.6 Soil water vapor sorption isotherms (WSIs)

The measurement of water repellency in the laboratory can take around four to six weeks, which is laborious. So, faster alternative methods are necessary to estimate the degree of SWR and functional SWR parameters described in Figure 13. Soil water vapor sorption isotherms (WSIs) can estimate SWR$_{AREA}$ (Figure 15) and w$_{NON}$ and their relationship with water content, organic carbon and clay content. Three on the main factors that control water repellency (Hermansen et al., 2021a).

![Figure 15. Comparison of (a) water vapor sorption isotherms and (b) soil water repellency (WR) as a function of gravimetric water content for two soil samples with differing clay (CL) and OC contents (kg kg$^{-1}$). The hysteresis of the isotherm is equivalent to the SWR$_{AREA}$ (Hermansen et al., 2021a).](image-url)
3 METHODOLOGY

3.1 Location of experimental fields

This study is comprised of 127 samples distributed across several fields of Greenland and Denmark (Table 3). Two fields located in Upernaviarsuk (60°44′57.3″N, 45°53′24.4″W) and South Igaliku (60°53′15.2″, N 45°16′37.1″W) in South Greenland (Figure 16a-b). They were established in 2018 and 2019, situated between the Greenlandic ice sheet and the Labrador Sea, close to the fjords (Weber et al., 2021).

In Denmark, peat soils from several fields distributed across Mid Jutland region, located in Skalså (56° 33′ 22.3″ N, 09° 46′ 07.3″ E), Nørreå (56° 26′ 13.7″ N, 09° 30′ 24.5″ E) and Odder (55° 56′ 09.6″ N, 10° 07′ 15.4″ E) were used (Figure 17).

In addition, 12 samples from several sites in South Denmark were considered. Detailed information about Greenlandic point samples is provided in Weber et al., (2021).

3.2 Field characteristics

According to Weber et al., (2021), the two fields analyzed in South Greenland were used for hay production with perennial grasses for more than 50 years. These areas included native vegetation, represented by grass mixtures of e.g., colonial bentgrass (*Agrostis tenuis* L.), Kentucky bluegrass (*Poa pratensis* L.), Perennial ryegrass (*Lolium perenne* L.), and white clover...
(Trifolium repens). Both fields have not been tilled the last three years. The extent of the fields is 1ha per each one, and they are located inside of “Kujataa” -the UNESCO world heritage site-, declared in 2017 to protect the agricultural activity and its history, dated back as the Norse Landnám c.a. 985 CE (UNESCO, 2017; Weber et al., 2020).

These agricultural fields are characterized by being ice-free areas, not affected by permafrost, and by having suitable soil moisture, and adequate microclimates. The climate is oceanic with a mean annual temperature from - 6°C to 10.7°C and the mean annual precipitation is 612.9mm. (Weber et al., 2020; Danish Meteorological Institute, 2021).

The Danish peat soils located in the Mid Jutland region were used for agricultural production. These soils were collected during the SINKS sampling campaign in 2020. The purpose of the SINKS sampling campaign was to collect peat soils from lowland areas of Denmark that are still affected by agricultural production. The mean annual temperature ranges from 5.5°C to 12°C and the annual precipitation is 978mm (Danish Meteorological Institute, 2021).

3.3 Experimental design

3.3.1 Greenlandic glacial rock flour field-study

In Greenlandic soils, the two fields were divided into several plots of 9 m², which were sampled and labeled as pretreatment (Table 3). Afterward, glacial rock flour (GRF) concentrations of 0 t ha⁻¹, 50 t ha⁻¹,100 t ha⁻¹,300 t ha⁻¹, and 500 t ha⁻¹ were added and mixed along with the soil. The GRF concentrations were replicated four and three times as is shown in Figure 16a-b for fields 1300 and 3100, respectively. The location and the concentration of GRF in the two experiment fields were selected randomly. The vertical and horizontal distance between samples is 2m and 3m independently.

After the application of GRF, the two fields were resampled with an interval of one year. Samples were collected during two sampling campaigns in August of 2019 and 2020 (Table 3).
Figure 16. Location of two agricultural fields across the South of Greenland. Experimental sampling grid of a) 3100 and b)1300 field with Glacial rock flour (GRF) concentration from 0 to 500 t ha\(^{-1}\). Field 3100 contains 15 samples (S1-S15) and field 1300 20 samples (S1-S20).

### 3.3.2 South Greenlandic (GR-S) point samples

In addition to the 90 samples explained above, 12 samples from several sites in South Greenland were analyzed. According to Hermansen et al., (2021) & Weber et al., (2021), these samples were obtained in August between 2015 and 2018 from eight agricultural fields (Table 3).

### 3.3.3 Danish peat (DK) soils

For peat soils in Denmark, the sampling points coordinates were selected randomly (Error! Reference source not found.). A total of 25 samples were collected aleatorily in August 2020 as is shown in Table 3.

<table>
<thead>
<tr>
<th>Location</th>
<th>Field</th>
<th>Code</th>
<th>Year</th>
<th># Samples</th>
<th>GRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Greenland: Upernaviarsuk</td>
<td>1300</td>
<td>1300_1: Pretreatment</td>
<td>2018</td>
<td>20</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1300_4: First year</td>
<td>2019</td>
<td>20</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 3. Experimental fields
### 3.4 Soil sampling

Approximately 2 kg of disturbed soils were sampled per plot from fields 1300 and 3100 without and with GRF concentrations per year as described in Table 3. They were collected from the A-horizon directly below the turf at 5-15 cm soil depth. The same sampling procedure was applied for Greenlandic point samples by Weber et al., (2021).

For Danish peat soils, a box sample per point was collected within the first 10 cm of the topsoil in the SINKS sampling campaign.

Afterward, all samples were stored and air-dried in the laboratory of Aarhus University-Foulum.

### 3.5 Laboratory measurements
For the purpose of this study water repellency and soil water vapor sorption isotherms (WSIs) were measured in the laboratory. This was done to a total of 45 samples for water repellency and 25 for isotherms.

### 3.5.1 Soil water repellency measurements

Figure 13 shows the process to measure soil water repellency, both for DK and GR-S soils. With the data obtained, the soil water repellency versus water content (SWR-w) curve was calculated.

a) Air-dried soil

The 2kg of soil was air-dried in a well-ventilated laboratory at 20°C for approximately 2 weeks or around 8 weeks in the case of peat soils (Figure 18a).

b) Soil sieved

Once the soil was dried out, it was dry sieved to <2mm (Figure 18b). During sieving, special attention was given to small glacial rock flour particles. The samples were kept in plastic bags, properly labeled, and conserved in the laboratory. Furthermore, 10 or 15g of soil per sample was used to calculate water repellency from dried to saturated soil.

c) Subsamples preparation

Soil subsamples at standardized pretreatment after dried at 105°C, 60°C, and AD (air-dried) conditions were prepared. Subsamples were oven-dried for 24 hrs. at 105°C, then stored in a desiccator until measurement. In the same way, subsamples were dried for 24 hrs. at 60 °C, but they were stored at laboratory room conditions (20°C) for a minimum of 48 hrs. In this way, samples pretreated at 60°C obtain a water
content between 105°C and AD. In addition, 7 or 9 AD soil subsamples with 10 or 15g (depending on the amount of soil available) were used to cover dry to the saturated point in the soils. Therefore, a total of 10 or 12 subsamples per plot were processed in plastic bags (Figure 18c).

Intending to measure SWR at specific soil water contents \( (w) \) intervals from AD to \( W_{\text{NON}} \), as it is shown in Figure 18d. Estimated \( w \) (see calculations), was added to AD soil subsamples. Then it was mixed with the soil and shaken in the bags to ensure uniform distribution of the water. After adding demineralized water per each subsample, they were preserved in the fridge at 4°C for two weeks. It was mixed and shaken twice during that period.

Different concentrations of ethanol and deionized solutions were made. As is shown in figure 4e, demineralized water (0% ethanol) up to 45% of ethanol were used in the study. A set of 50 bottles with ethanol concentration increasing by 1% were available to use.

The severity of SWR was measured by molarity of an ethanol droplet (MED) test (de Jonge et al., 1999; Kawamoto et al., 2007; King, 1981; Roy & McGill, 2002) using the same method as Hermansen (2019).

In short, around ±5 g of soil was immediately placed in a disposable sample cup lid (white container in Figure 18f). With the help of a small knife, the surface was uniformed smooth. Thereupon, the sample was subjected to the
normal stress of 60.9 Nm (black+ blue object) for 2 min. Then 60 μL droplet of ethanol solution was used over the surface of a soil sample and left to infiltrate for five seconds. The process was repeated to find the highest ethanol concentration that did not infiltrate in the soil within five seconds. At that point, the percentage of ethanol measured was used to calculate the surface tension of the soil sample following Roy & McGill (2002) and Hermansen (2019) methodology. The degree of water repellency is calculated.

e) Soil water content

Finally, around ±7 to ±10g of soil per each subsample was immediately weighed and placed in an aluminum container (Figure 18e), and after, oven-dried for 24 hours at 105°C to calculate its soil water content, followed by cooling in a desiccator.

Figure 18. The gradual process to measure soil water repellency for South Greenlandic (GR-S) and Danish peat (DK) soils. The same process was applied for pretreatment samples, as well as for soil with GRF concentrations.

In addition to SWR, the texture and organic carbon (OC) of the samples were analyzed. The texture was determined by the wet-sieving together with the pipette method, after the removal of SOM. ELTRA Helios C-Analyzer was used to determine OC concentration by high-temperature dry combustion. Both values were obtained from Weber et al., (2021).

3.5.2 Water vapor sorption isotherm measurements

Figure 14 shows the process to measure soil water vapor sorption isotherms (WSIs) at 25°C in air-dry samples via adsorption and desorption for the relative humidity (RH) range from 3% to 93%, using an automated vapor sorption analyzer (VSA). DK and GR-S soils were measured following the same procedure.
a) Soil sample preparation

The aluminum cub needs to be cleaned before it is used. Then, it is weighted and calibrated in the VSA Isotherm Generator. Afterward, around ±7 g of AD soil was added, maximum up to half of the cup (Figure 19a) and weighed again. Finally, the borders of the cup should be cleaned as well as its outside.

b) Sample measurement

Put the soil sample in the VSA Isotherm Generator. The weight of the sample shown on the screen should be recorded, and the measurement starts.

c) Oven-dried soil.

After finishing the measurement, the soil sample is oven-dried at 105°C for 48hrs. and weighted to calculate its water content.

Figure 19. Process to measure moisture sorption isotherms in the VSA Isotherm Generator for South Greenlandic and Danish peat soils. The same process was applied for pretreatment samples, as well as for soil with GRF concentrations.

3.6 Calculations

3.6.1 Soil water repellency versus water content curves

The specific amount of water to add to per each soil subsample was calculated based on earlier experiences with moistening soil samples used by Hermansen, Moldrup, Müller, Jensen, et al., (2019b); Hermansen, Moldrup, Müller, Knadel, et al., (2019b); Hermansen et al., (2021); Weber et al., (2021).

As is shown in Table 4, the amount of water to add to each subsample varies in DK soils. The same principle was applied to GR-S soils.

Table 4. Moisture plan for Danish peat (DK) soils
After soil moisturizing and SWR measurement as described in Figure 18, the SWR area is calculated using the following equations:

\[ SWR_{n+n+1} \text{ (mol l}^{-1}\text{)} = 0.1713 \times SWR\text{\%}_\text{ethanol} \quad \text{Equation (1)} \]

\[ SWR_{n+n+1} \text{ (mol l}^{-1}\text{)}: \text{SWR in molarity of ethanol of the subsample n.} \]

0.1713: constant

\[ SWR\text{\%}_\text{ethanol}: \text{percentage of ethanol obtained after measuring SWR in the laboratory} \]

\[ SWR_{n+n+1} \text{ (mN m}^{-1}\text{)} = 61.05 - 14.75 \ln * (SWR_n \text{ (mol l}^{-1}\text{)} + 0.5) \quad \text{Equation (2)} \]

(Roy & McGill, 2002) if \( SWR \text{ (mol l}^{-1}\text{)} < 6 \)

\[ SWR_{n+n+1} \text{ (mN m}^{-1}\text{)} = 52.716 - 10.7 \ln * SWR_n \text{ (mol l}^{-1}\text{)} \quad \text{Equation (3)*} \]

(Hermansen, 2019) if \( SWR \text{ (mol l}^{-1}\text{)} > 6 \)

\[ SWR_{n+n+1} \text{ (mN m}^{-1}\text{)}: \text{degree of SWR in the unit of liquid surface tension of ethanol, the molarity of ethanol of the subsample n.} \]

*Equation 3 was used for soils with a high amount of organic carbon. That was the case for some DK soils.
\[ SWR_{\text{AREA}}_{n,n+1} (mN m^{-1} kg kg^{-1}) = (w_n - w_{n+1}) \times \frac{(SWR_{n+1} + SWR_n)}{2} \]  \hspace{1cm} \text{Equation (4)}

\[ SWR_{\text{AREA}}_{n,n+1} (mN m^{-1} kg kg^{-1}) \] trapezoidal integrated area under the curve.

As the SWR\(_{\text{AREA}}\) is first calculated between each increment in water content, the total soil water repellency area is the summary of the individual \(SWR_{\text{AREA}}\) of soil at 105°C, 60°C, AD, and \(SWR_{\text{AREA}}\) in the interval from AD to \(W_{\text{NON}}\).

The \(W_{\text{NON}}\) is found when the soil becomes hydrophilic, at 0% of ethanol (Figure 13).

Finally, the SWR (mN m\(^{-1}\)) point values are plotted as a function of soil water content (\(w\)), leading to the SWR-\(w\) curve (Figure 13).

### 3.6.2 Water vapor sorption Isotherms

Soil water content was determined at respective RH values. Further description of the methodology used is provided in Arthur et al. (2014).

To normalize the SWR\(_{\text{AREA}}\) from the dry soil water retention in south Greenlandic soils, the simple semi-logarithmic Campbell-Shiozawa (CS) model was applied by Webber et al. (2022). As a result, the dimensionless slope of the pF-W relationships was calculated (\(α\)) and the normalization was performed by dividing SWR\(_{\text{AREA}}\) to the inverse negative CS-slope (\(-α^{-1}\)). A depth description of the procedure can be found in the scientific paper attached in the appendix section.

### 3.7 Statistical Analysis

To examine water repellency as a function of water content in South Greenlandic soils and compare it to Danish peat soils:
Descriptive statistical analysis was used to examine functional SWR parameters ($SWR_{\text{AREA}}$, $w_{\text{NON}}$, $WR_{\text{AD}}$ and $WR_{60^\circ\text{C}}$) and soil properties (texture and OC) from South Greenlandic (GR-S) and Danish peat (DK) soils. GR-S soils involve fields 1300_1, 3100_1, and GR.

Since the distribution of the data was not parametric, spearman rank-order correlation coefficient was used for determining which soils properties control water repellency for both GR-S and DK soils. Further, OC was correlated with functional SWR parameters using simple lineal and non-simple lineal regression.

For non-lineal regression model, package GLM in RStudio was performed to investigate the probability distribution of the data. Then, a sigmoidal function that was a better fit on the data was run in the program SigmaPlot 14. The following function describes the three Parameter Gompertz Growth Model:

$$y = a e^{-e^{\left(-\frac{x-x_0}{b}\right)}}$$

$a, x_0, b$: fitted parameters
$e$: Euler's Number

Gompertz function is asymmetrical and describes a slow growth at the begging of the curve, which is accelerated up to reach a horizontal asymptote at the end of the curve (Gregory et al., 2006).

To investigate the effect of the use of Glacial rock flour (GRF) as a soil amendment on the water repellency of Greenlandic soils:

Due to the small sample size, error bars were used to show the effect of GRF addition on functional SWR parameters and soil properties each year of treatment and per field. The difference between treatment and pretreatment was plotted.

Because the experiment was conducted in field experiments (non-controlled settings), Wilcoxon Signed-rank test, a non-parametric test equivalent to paired t-test, was used to determine if the functional SWR parameters and soil properties changed over the first year of treatment.

As the distribution of data was non-parametric, Kruskal-Wallis by rank was used to determine the effect of different GRF concentrations on SWR parameters and soil
properties. In the same way, Wilcoxon rank-sum test along with Bonferroni correction was performed to establish any significant effect.
4 RESULTS AND DISCUSSION

4.1 Soil water repellency (SWR) in Subarctic and Temperate soils

4.1.1 Water repellency parameters and soil properties

As the MED test uses ethanol solution concentrations, where ethanol reduces the surface tension of deionized water (72.27 mN m\(^{-1}\)) at 20°C. Lower surface tension of the ethanol solution means higher severity of SWR (Figure 13). Thus, surface tension of water was subtracted from water repellency after bring air dried (WR\(_{\text{AD}}\)) and oven dried at 60°C (WR\(_{60^\circ C}\)) to reverse the relationship, e.g., water repellency at AD conditions is presented as 71.27-WR\(_{\text{AD}}\), and at 60°C as 71.27-WR\(_{60^\circ C}\).

South Greenlandic (GR-S) soils covered coarse and medium textured soil types (Figure 20). Field GR covered mostly sandy loam soil texture class and some loam class. Fields 1300_1 and 3100_1 were mainly distributed across sandy loam class, and to less extent across loamy sand textured class. Similar soil textures have been found in the south of Greenland by Gregory et al., (2006;) Hermansen et al., (2017); and Weber et al., (2020). Soils from Denmark (DK) were classified as peat soils.

![Figure 20. Distribution of the soil texture of South Greenlandic (GR) soils across the USDA soil texture triangle.](image-url)
All the 72 soil samples analyzed, both DK (n=25) and GR-S (n=47) were water repellent. The functional SWR parameters: total degree of water repellency (\(\text{SWR}_{\text{AREA}}\)), critical soil water content, where the soil becomes hydrophilic (\(w_{\text{NON}}\)), \(\text{WR}_{\text{AD}}\), and \(\text{WR}_{60°C}\) increased along with OC content in the following sequence: field 3100_1 (n=15), field 1300_1 (n=20), field GR (n=12), and Danish peat (DK) soils (n=25) (Figure 21).

The OC content in GR-S soils ranged from 0.01 to 0.24 kg kg\(^{-1}\), while DK soils showed a greater range with values from 0.02 to 0.43 kg kg\(^{-1}\) (Table 5). Thus, DK soils exhibited a remarkable variability in the \(\text{SWR}_{\text{AREA}}\) and \(w_{\text{NON}}\) (Figure 21a). Therefore, the severity of water repellency in DK and GR-S soils is dependent on OC content. Similar results were found by Hermansen, Moldrup, Müller, Jensen, et al., (2019) in soils from New Zealand where \(\text{SWR}_{\text{AREA}}\), \(w_{\text{NON}}\), and \(\text{WR}_{60°C}\) intensity increased or decreased in conjunction with OC content (0.02–0.21 kg kg\(^{-1}\)), and \(\text{SWR}_{\text{AREA}}\) and \(w_{\text{NON}}\) in Japan from sandy loam to organic soils (0.006–0.26 kg kg\(^{-1}\)) by Wijewardana et al., (2016).

The potential water repellency (\(\text{WR}_{\text{AD}}\) and \(\text{WR}_{60°C}\)) in DK soils were higher than GR-S soils (Table 6). However, GR-S soils, specifically field GR, reached maximum values close to DK soils (Figure 21c, d). Therefore, the increase of the severity of SWR during dry periods affects both coarse and organic soils.

Sandy soils are more susceptible to develop water repellency, due to its low amount of clay, and small surface area (Doerr et al., 2000). However, despite its texture, GR-S soils had an important amount of OC in a non-complexed form (\(n\)-radio <1.5), which has been reported also by Pesch et al., (2020) and Hermansen et al., (2016). In addition, SWR has been found to be more correlated with non-complexed OC than itself in Danish soils by de Jonge et al., (2009). Further, according to Weber et al., (2021), colonial bentgrass (\textit{Agrostis tenuis} L.) is present in the two fields analyzed from South Greenland, which has been recognized as a grass species that induces water repellency (Doerr et al., 2000).

Organic material responsible for water repellency is mor-type humus and litter (Doerr et al., 2000), so soils developed in environments with slow natural decomposition rate (GR-S soils) and/or high degree of humification (DK soils) are prone to develop water repellency. Specifically for peat soils, water repellency is influenced by organic content, moss species, water content, and fire conditions (Wu et al., 2020).
Table 5. Descriptive statistics of the physical properties of South Greenlandic (GR-S) and Danish peat (DK) soils: organic carbon (OC), critical soil-water content ($w_{NON}$), total degree of soil water repellency ($SWR_{AREA}$), water repellency after soil dried at 60°C ($71.27$-$WR_{60^\circ C}$) and air dried ($71.27$-$WR_{AD}$)

<table>
<thead>
<tr>
<th>Field</th>
<th>n</th>
<th>OC (kg kg$^{-1}$)</th>
<th>SWR$_{AREA}$ (mN m$^{-1}$ kg kg$^{-1}$)</th>
<th>$w_{NON}$ (kg kg$^{-1}$)</th>
<th>$71.27$-$WR_{60^\circ C}$ (mN m$^{-1}$)</th>
<th>$71.27$-$WR_{AD}$ (mN m$^{-1}$)</th>
</tr>
</thead>
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<td>South Greenlandic soils</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.05</td>
<td>6.69</td>
<td>0.17</td>
<td>8.78</td>
<td>8.06</td>
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<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>25.89</td>
<td>0.92</td>
<td>35.73</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.01</td>
<td>0.88</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.06</td>
<td>5.48</td>
<td>0.20</td>
<td>12.73</td>
<td>4.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>2.87</td>
<td>0.11</td>
<td>4.34</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.09</td>
<td>9.05</td>
<td>0.34</td>
<td>18.04</td>
<td>14.22</td>
</tr>
<tr>
<td>Danish peat soils</td>
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<td>22.55</td>
<td>0.77</td>
<td>25.91</td>
<td>25.62</td>
</tr>
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<td></td>
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</tr>
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</tr>
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<td>1.64</td>
<td>0.09</td>
<td>4.34</td>
<td>10.43</td>
</tr>
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<td>26.58</td>
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<td>26.76</td>
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</tr>
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<td>0.13</td>
<td>10.23</td>
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</tr>
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<td>0.35</td>
<td>31.48</td>
<td>1.15</td>
<td>30.39</td>
<td>29.72</td>
</tr>
</tbody>
</table>

Specifically in soils from south of Greenland, field GR with an OC that ranged between 0.01 and 0.24 kg kg$^{-1}$ and a mean of 0.11 ±0.07 kg kg$^{-1}$, displayed the highest OC content (Table 6). Nevertheless, it presented a right-skewed distribution (Figure 21c), i.e., 50% of the soil samples were spread between 0.13 and 0.24 kg kg$^{-1}$. Thus, $SWR_{AREA}$ and $w_{NON}$ varied as OC did. Field 3100_1 showed the lowest OC content with 0.02 ±0.01 kg kg$^{-1}$. Fields 3100_1 and 1300_1 exhibited normal distributions (Table 6). Similar to DK soils, $SWR_{AREA}$ and $w_{NON}$ in the three fields ranked from low to high following OC contents: field 3100_1, field 1300_1, and GR (Figure 21a-b) (Table 6). In the south of Greenland equal small-scale OC variations have been reported by Ogrič et al., (2019) with an OC range between 0.006-0.40 kg kg$^{-1}$ in 176 samples, and across 23 agricultural fields by (Weber et al., 2020) with a range of 0.009-0.24 kg kg$^{-1}$. Such variations are associated with climatic gradient, topography, hydrology, etc. (Ogrič et al., 2019) and Arctic soil genesis, dominated by cryogenic process (Margesin, 2009; Ping et al., 2015; Tedrow, 2005).

The potential water repellency in dry soils ($WR_{AD}$, $WR_{60^\circ C}$), followed the same trend in the GR-S fields which were previously described. Field 3100 had a right-skewed distribution (Figure 21 d-e), i.e., at least 50% of the samples were non-water repellent after being air dried and
oven dried at 60°C. It has been suggested that MED test measures the abundance and the intensity of the interaction between soil surface and fatty acids (hydrophobic compounds). In that sense, temperature can reorientate and redistribute fatty acids, rising SWR degree; and/or evaporate or even polymerize them; so, reducing repellency (Graber et al., 2009). Therefore, as hydrophilic behavior has been observed in dried soils with the lowest OC value (Table 6), SWR in subarctic soils depends on both type and amount of OC. Similar divergences of the effect of heating on SWR have been found by Doerr et al., (2005) in soils with OC values lower than 0.03 kg kg⁻¹.

Table 6. Descriptive statistics of the physical properties of south Greenlandic (GR-S) fields: organic carbon (OC), critical soil-water content (W_NON), total degree of soil water repellency (SWR_AREA), water repellency after soil dried at 60°C (71.27 - WR60°C) and air dried (71.27 - WRAD)

<table>
<thead>
<tr>
<th>Field</th>
<th>n</th>
<th>Stat.</th>
<th>OC (kg kg⁻¹)</th>
<th>SWR_AREA (mN m⁻¹ kg⁻¹)</th>
<th>W_NON (kg kg⁻¹)</th>
<th>71.27-WR60°C (mN)</th>
<th>71.27-WRAD (mN m⁻¹)</th>
</tr>
</thead>
<tbody>
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<td>3100_1</td>
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<td>Mean</td>
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<td>0.09</td>
<td>5.04</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
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<td>0.77</td>
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<td>7.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max</td>
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<td>24.06</td>
<td>25.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
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<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Median</td>
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<td>2.01</td>
<td>0.08</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q1</td>
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<tr>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td>7.92</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>35.73</td>
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</tr>
<tr>
<td></td>
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</table>
4.1.2 Soil water repellency versus water content (SWR-w) curves

Soil water repellency (SWR) versus water content (w) curves for GR-S and DK soils are shown in Figure 22 and Figure 23. They were sorted according to increasing OC values. In this section the field GR was not considered.

GR-S soils displayed unimodal and bimodal curve types described by de Jonge et al., (1999) (Figure 14), while DK soils displayed only bimodal shape. Unimodal curves counted for 5% of the soil samples in Greenland, where after air dry (wAD), and oven dry conditions at 60°C (w60°C) and 105°C, the soil was hydrophilic or hydrophobic. Then, the severity of repellency increased with w up to reaching its maximum (WRMAX) before becoming completely
hydrophilic ($w_{NON}$) (Figure 22a-b). For bimodal curves, the first peak was developed in the dry conditions, the maximum degree was observed at $WR_{105^\circ C}$, which declined and/or reached hydrophilic conditions. Then, the second peak started and increased at $w > w_{AD}$, following the same behavior of the unimodal curve. For both, DK and GR-S soils, the $WR_{MAX}$ was reached in the second peak (Figure 22 and Figure 23).

Most studies based SWR measurements in AD soils. However, the degree of repellency varies with soil moisture and the $WR_{MAX}$ is found between wilting point and field capacity (Hermansen, Moldrup, Müller, Jensen, et al., 2019; Kawamoto et al., 2007; Wijewardana et al., 2016). In the same way, in a study in peat soils conducted by Moore et al., (2017) the severity of water repellency was approximately equal in air dried soils and saturated soils followed by air-dried for 29 days, revealing within that period of time different variations in the degree of repellency across $w$. For that reason, it is important to measure water repellency across $w$ intervals instead of dry conditions since it may lead to an underestimation of severity. For example, in the present study GR-S soils would be classified as hydrophilic and DK soils as very strongly hydrophobic, according to the classification developed by Doerr (1998) (Table 2), if just $WR_{AD}$ is contemplated, but when the $w$ interval, where the soil is hydrophobic, is considered, i.e., integrative repellency dynamic index (IRDI), $SWR_{AREA} \times w_{NON}^{-1}$ (Hermansen, Moldrup, Müller, Jensen, et al., 2019), both soils would be classified as very strongly hydrophobic.

In DK soils, temporally hydrophilic behavior in the dry area was not reached a difference of Greenlandic soils, where approximately 40% of the soil samples where hydrophilic either at $w_{60^\circ C}$ and/or $w_{AD}$.

As the severity of water repellency in DK and GR-S soils is dependent of OC content, SWR-$w$ curves showed $SWR_{AREA}$ and $w_{NON}$ increased along with OC content for Greenlandic (Figure 22) and DK soils (Figure 23). Equivalent results were found by Weber et al., (2021) in 145 soil samples from 22 subarctic agricultural fields in the south of Greenland, where water repellency across the SWR-$w$ curve was influenced by OC values.

In the same way, $WR_{60^\circ C}$ and $WR_{AD}$ was greater for high OC values, i.e., in Greenlandic soils from 0.01 to 0.07 kg kg$^{-1}$ of OC (Figure 22a-d) most of the samples at $w_{60^\circ C}$ and/or $w_{AD}$ reached hydrophilic conditions (71.27 mN m$^{-1}$), but while OC increased this characteristic started to
disappear (Figure 22e-f). This phenomenon was more evident in DK soils (Figure 23) due to its wider OC range. Even in some SWR-w curves the reduction of the length of the first peak was observed, providing the idea of a possible shift in the shape curve from bimodal to unimodal. Therefore, the degree of repellency in dry soils is influenced by both type and amount of OC.
Figure 22. Soil water repellency (SWR) as a function of soil water content (w) for South of Greenlandic soils (fields 1300_1 and 3100_1). Curves plotted with increasing organic carbon (OC) content in subplots a-f. SWR-w curves in yellow dots are unimodal and in green dots are bimodal curves.
Figure 23. Soil water repellency (SWR) as a function of soil water content (w) of Danish peat soils. Curves are plotted with increasing organic carbon (OC) content in subplots a-f. The complete set of peat soils displayed bimodal curves.
4.1.3 Soil factors controlling water repellency.

Clay, silt, and OC content had moderate to very strong positive correlation with all four SWR functional parameters in GR-S soils, SWR\textsubscript{AREA}, w\textsubscript{NON}, WR\textsubscript{AD}, and WR\textsubscript{60°C}. For sand, the correlation was moderate to strong with SWR\textsubscript{AREA} and w\textsubscript{NON} (Table 7). In the case of silt content, a distinction was made between fine and coarse silt, while fine silt had a strong positive correlation with all SWR parameters, coarse silt did not show any significant correlation. In the same way, the correlation between SWR\textsubscript{AREA} and w\textsubscript{NON} with fine sand was strong and negative, while with coarse sand it was moderately positive. The role of soils texture in SWR differs among different studies, e.g., in soils from New Zealand, soil particles showed a weak or no significant correlation with SWR parameters (Hermansen, Moldrup, Müller, Jensen, et al., 2019). In sandy soils from south of Denmark, WR\textsubscript{60°C} had a moderate positive correlation with clay and coarse sand, and a strong negative with fine sand (Knadel et al., 2016).

According to (Dexter et al., 2008), soils with clay content < 10%, as GR-soils are, prone to develop SWR, since complexed clay (n< 10) is not dispersible in water. Further, in soils with important amount of organic carbon, the number of hydrophobic coatings can be great enough to cover both the coarse and fine-sized particles; thus, fine-sized soils can be even more water repellent than coarse soils (Doerr et al., 2000). For example, de Jonge et al. (2009) found an increment in the degree of SWR with the decrease of size fraction in grass crop from Denmark, in small fractions <63 µm and between 63–125 µm. Consequently, as GR-S texture had the same correlation with both OC and SWR parameters, the OC is the main driver of SWR in these soils.
Table 7. Spearman rank-order correlation coefficient (p<0.05) matrix of South Greenlandic soils (n=47) characteristics: organic carbon (OC), critical soil-water content (wNON), total degree of soil water repellency (SWRAREA), water repellency after dried at 60°C (71.27 mN m⁻¹-WR₆₀°C), and air dried (71.27 mN m⁻¹-WRAD), clay (<2μm), fine silt (2-20 μm), coarse silt (>20-60μm), fine sand (>60-200μm), and coarse sand (>0.2-2m).

<table>
<thead>
<tr>
<th></th>
<th>OC</th>
<th>WNON</th>
<th>SWRAREA</th>
<th>71.27-WR₆₀°C</th>
<th>71.27-WRAD</th>
<th>Clay</th>
<th>Fine silt</th>
<th>Coarse silt</th>
<th>Fine sand</th>
<th>Coarse sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC</td>
<td>1</td>
<td>0.97</td>
<td>0.98</td>
<td>0.74</td>
<td>0.61</td>
<td>0.92</td>
<td>0.81</td>
<td>-0.75</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>WNON</td>
<td>1</td>
<td>0.98</td>
<td>0.65</td>
<td>0.56</td>
<td>0.93</td>
<td>0.78</td>
<td>-0.80</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWRAREA</td>
<td>1</td>
<td>0.71</td>
<td>0.62</td>
<td>0.92</td>
<td>0.80</td>
<td>-0.77</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>71.27-WR₆₀°C</td>
<td>1</td>
<td>0.90</td>
<td>0.59</td>
<td>0.78</td>
<td>0.29</td>
<td>-0.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>71.27-WRAD</td>
<td>1</td>
<td>0.51</td>
<td>0.69</td>
<td></td>
<td>-0.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>1</td>
<td>0.76</td>
<td></td>
<td></td>
<td>-0.77</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine silt</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>-0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse silt</td>
<td></td>
<td>1</td>
<td>0.54</td>
<td>-0.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine sand</td>
<td></td>
<td>1</td>
<td>-0.86</td>
<td></td>
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<tr>
<td>Coarse sand</td>
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</tbody>
</table>

In DK soils, OC had a very strong correlation with SWRAREA and WNON. However, despite the higher OC contents in DK soils in comparison with GR-S soils, its correlation with WRAD, WR₆₀°C is moderate (Table 8 Error! Not a valid bookmark self-reference.). Hence, SWRAREA and WNON was directly proportional to OC values, but for WRAD and WR₆₀°C the relationship was non-linear.

Table 8. Spearman rank-order correlation coefficient (p<0.05) matrix of Danish peat soils (n=25) characteristics: organic carbon (OC), critical soil-water content (WNON), total degree of soil water repellency (SWRAREA), water repellency after dried at 60°C (71.27 mN m⁻¹-WR₆₀°C), and air dried (71.27 mN m⁻¹-WRAD).

<table>
<thead>
<tr>
<th></th>
<th>OC</th>
<th>WNON</th>
<th>SWRAREA</th>
<th>71.27-WR₆₀°C</th>
<th>71.27-WRAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC</td>
<td>1</td>
<td>0.92</td>
<td>0.95</td>
<td>0.49</td>
<td>0.54</td>
</tr>
<tr>
<td>WNON</td>
<td>1</td>
<td>0.96</td>
<td>0.40</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>SWRAREA</td>
<td>1</td>
<td>0.49</td>
<td>0.60</td>
<td></td>
<td>0.60</td>
</tr>
<tr>
<td>71.27-WR₆₀°C</td>
<td>1</td>
<td></td>
<td>0.93</td>
<td></td>
<td>0.93</td>
</tr>
<tr>
<td>71.27-WRAD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

As mentioned before, OC was very strongly correlated to the severity of water repellency for both DK and GR-S soils. OC content explained the 96% of variation of SWRAREA (Figure 24a) and
97% of variation of \( w_{NON} \) (Figure 24b). Hence, using a simple linear regression these relationships were expressed as:

\[
\text{SWR}_{\text{AREA}} = 94.13 \, OC + 0.02 \quad \text{Equation (5)}
\]

\[
\text{RSME} = 2.14 \, mN \, m^{-1} \, kg \, kg^{-1}
\]

\[
w_{NON} = 3.16 \, OC + 0.02 \quad \text{Equation (6)}
\]

\[
\text{RSME} = 0.09 \, kg \, kg^{-1}
\]

Similar linear correlations have been described for subarctic soils (0.009-0.24 kg kg\(^{-1}\)OC) with \( \text{SWR}_{\text{AREA}} \) and \( w_{NON} \) with \( r^2 = 0.91 \) and \( r^2 = 0.88 \) respectively (Weber et al., 2021); for temperate soils (0.021-0.21 kg kg\(^{-1}\)) with \( r^2 = 0.68 \) for both parameters (Hermansen, Moldrup, Müller, Jensen, et al., 2019); and \( r^2 = 0.68 \) for \( \text{SWR}_{\text{AREA}} \) in subarctic, temperate, and subtropical soils (0.01-0.80 kg kg\(^{-1}\)) (Regalado et al., 2008).

Hermansen, Moldrup, Müller & Jensen, et al. (2019) developed lineal expressions for water repellent soils from New Zealand: \( \text{SWR}_{\text{AREA}} = 100.6 \, OC - 0.088 \), RMSE: 2.09; \( w_{NON} = 3.08OC + 0.16 \), RMSE: 2.09. Applying these equations and equations 5 and 6, developed in this study, resulted in equal estimated \( \text{SWR}_{\text{AREA}} \) and \( w_{NON} \) values.

Figure 24. a) Total degree of soil water repellency (\( \text{SWR}_{\text{AREA}} \), and b) critical soil-water content (\( w_{NON} \)) as function of OC content. Samples from south of Greenland (GR) from Hermansen et al., (2021)

The degree of water repellency in dry soils was influenced by OC as shown in Figure 25, where at values <0.02 kg kg\(^{-1}\) the degree of \( \text{WR}_{\text{AD}} \) and \( \text{WR}_{60^\circ C} \) was low, then it rapidly increased along with OC up to reach its maximum degree around 0.25 kg kg\(^{-1}\) OC. Similar results were found
by Deurer et al., (2011), where WR\textsubscript{AD} was moderately related (r\textsuperscript{2}=0.45) with OC values between 0.03-0.15 kg kg\textsuperscript{-1}; however, at larger OC amounts the relationship became weak. In the same way, for WR\textsubscript{60°C} Knadel et al., (2016) obtained a weak correlation at low OC contents 0.01-0.02 kg kg\textsuperscript{-1}.

OC explained the 71% of the variation of WR\textsubscript{60°C} (Figure 25a) and 66% of WR\textsubscript{AD} (Figure 25b). The relationship between water repellency in dry soils and OC content were expressed with Gompertz function as:

\[
71.27 - \text{WR\textsubscript{60°C}} = 28.05 e^{-e^{-\frac{(OC-0.05)}{0.05}}}
\]

\[RSME = 5.62 mN m^{-1}\]

\[
71.27 - \text{WR\textsubscript{AD}} = 28.70 e^{-e^{-\frac{(OC-0.08)}{0.07}}}
\]

\[RSME = 6.75 mN m^{-1}\]

\[\text{Equation (7)}\]

\[\text{Equation (8)}\]

\[
\text{Figure 25. a) Soil water repellency dried at } 60^\circ\text{C, and b) Soil water repellency at air dried conditions, both as function of OC content. Samples from south of Greenland (GR) (Hermansen et al., 2021b). Note that surface tension of water (71.27 mN m\textsuperscript{-1}) was subtracted to reverse the relationship.}\]

It is widely recognized that heating enhances water repellency in soils, since it reorganizes the position of amphiphilic molecules, i.e., the hydrophilic ends interact with the soil surface or between them, leaving the hydrophobic end exposed, and the chemical bonding between organic material and minerals is heightened after heating (Doerr et al., 2000; Hermansen, Moldrup, Müller, Jensen, et al., 2019; Wijewardana et al., 2016). However, in this study, the
enhancement of repellency by the temperature at 60°C was less extended in soils with very low and very high OC values (Figure 25). WR_{60°C} increased 50% in field 1300_1 (Table 6), and 30% in field GR (p = <0.001) in comparison to WR_{AD} (Table 5), while in field 3100_1 (lowest OC) and DK soils (highest OC) the effect was negligible (p>0.5). Similar results were found by Moore et al. (2017), where the mean persistence of SWR was almost equal for WR_{65°C} and WR_{AD} in peatlands in Canada.

The reason behind the aforementioned behavior may be that the intensity of water repellency in soils after being oven dried at 60°C is minor due to the small number of amphiphilic molecules that can reorganize. Another possibility is that they have already changed in air dried conditions in soils with low OC values and for high OC values. Following that reasoning, the soil surface could already be saturated with such molecules.

### 4.1.4 Conclusion

In this study 72 soil samples distributed across four agricultural fields from Denmark and south of Greenland were analyzed. From this section it is concluded that:

- The degree of water repellency for Danish peat soils (n=25) and south Greenlandic soils (n=47) was very strong.
- Functional SWR parameters: SWR_{AREA}, w_{NON}, WR_{AD}, and WR_{60°C} were higher in Danish peat soils, so they have a bigger potential to develop strong hydrophobicity under dry conditions.
- OC and soil moisture were the main drivers of water repellency in both soils. Soil texture also influenced the degree of hydrophobicity for south Greenlandic soils.
- OC explained the 96% and 97% of the variability of SWR_{AREA} and w_{NON} in both mineral and organic soils. WR_{AD} and WR_{60°C} shown a sigmoidal relationship with OC. It explained the 65 and 71% of the variability respectively.
4.2 Effect of glacial rock flour (GRF) on Subarctic soils

To further strengthen the upcoming results of this section, it is worth mentioning that I’ve contributed to the paper Weber et al. (2022) while simultaneously writing this thesis. It is included in the appendix section. The contributions include doing laboratory work and preliminary data analysis. The paper is to be submitted to the Soil Science Society of America Journal. Some of the results presented in this section are related to the findings described in the paper.

Some alleviation technologies for water repellent soils have been investigated. For example: the use of surfactants as seed coating and tree tablets have increased infiltration and improved water availability; the use of zero tillage with disc openers have shown beneficial results in water infiltration; the addition of clay to cultivated sandy soils to enlarge soil reactive surface and hence cover hydrophobic waxes; the use of fungal microorganisms to reduce water repellency; the use of slow-release fertilizers to stimulate natural wax-degrading microorganisms; the addition of dissolved organic matter; and the use of GRF; among others, have been suggested (Blanco-Canqui & Ruis, 2018; Doerr et al., 2000; Kostka et al., 2009; Letey, 2005; Pesch et al., 2022; Ruthrof et al., 2019).

GRF has been studied in the last few years as a potential soil fertilizer. A study conducted by Gunnarsen et al., (2019) indicated an improvement in the growth of plants cultivated in soils mixed with rock flour, as a result of the slow release of potassium (K) and magnesium (Mg). Further, Sukstorf et al., (2020) reported an increased in yield production when GRF combined with an artificial N-P-K fertilizer is used as mineral fertilizer in Greenlandic soils.

The GRF used in the present study has been suggested as a good potential soil amendment by Pesch et al., (2022), due to its mineral composition, high cation exchange capacity, and specific surface charge. Also, it is characterized by having high amounts of fine particles (Table 9) and by being completely hydrophilic (Figure 26).
Table 9. Physical properties of the glacial rock flour organic (GRF) used as amendment in this study: organic carbon (OC), critical soil-water content ($W_{NON}$), total degree of soil water repellency calculated as integrated trapezoidal area underneath of SWR-w curve ($SWR_{AREA}$), surface tension of water (71.27 mN m$^{-1}$), soil water repellency after dried at 60°C and air dried ($WR_{60°C}$ & $WR_{AD}$), clay (<2µm), fine silt (2-20 µm), coarse silt (>20-60µm), fine sand (>60-200µm), and coarse sand (>0.02-2m).

<table>
<thead>
<tr>
<th>Field</th>
<th>OC (kg kg$^{-1}$)</th>
<th>$W_{NON}$ (kg kg$^{-1}$)</th>
<th>$SWR_{AREA}$ (mN m$^{-1}$ kg kg$^{-1}$)</th>
<th>$71.27$-WR$_{60°C}$ (mN m$^{-1}$)</th>
<th>$71.27$-WR$_{AD}$ (mN m$^{-1}$)</th>
<th>Clay (kg kg$^{-1}$)</th>
<th>Fine Silt (kg kg$^{-1}$)</th>
<th>Coarse silt (kg kg$^{-1}$)</th>
<th>Fine sand (kg kg$^{-1}$)</th>
<th>Coarse sand (kg kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRF</td>
<td>0.00</td>
<td>-</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.21</td>
<td>0.24</td>
<td>0.15</td>
<td>0.20</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Figure 26. SWR-w curve for Greenlandic soil (hydrophobic) and Glacial rock flour (GRF) (hydrophilic) applied in this study. For each sample, the $SWR_{AREA}$ was calculated to show the hydrophilic and hydrophobic characteristics.

4.2.1 Soil water repellency versus water content (SWR-w) curves

The effect of the four GRF concentrations: 50, 100, 300 and 500 t ha$^{-1}$ on field 3100 is shown in Figure 27. Related to the untreated control (0 t ha$^{-1}$), the characteristics of the SWR-w curve did not show any decrease between the first year of treatment and pretreatment (3100_1) (subplot a-c). With the addition of 300 and 500 t ha$^{-1}$ of GRF (subplot j-o) 83% of soil samples shown a reduction in the area under the curve and in the potential water repellency, $WR_{60°C}$ and $WR_{AD}$. At $w_{60°C}$ and $w_{AD}$ hydrophobic soil was rendered to hydrophilic and even in 50% of the samples this hydrophilic behavior was observed at $w > w_{AD}$ (subplot l, m, n). The $W_{NON}$
decreased only in one sample (subplot n). Further, the shift from bimodal to unimodal curve shape was observed in subplots (j) and (m).

In field 1300 (Figure 28), the SWR-w curve characteristics increased in the first year of treatment (1300_4) and then decreased in the second year (1300_5) in the control plots (subplot a-d). Nevertheless, with the addition of 300 and 500 t ha\(^{-1}\) of GRF (subplot m-s) this trend was disrupted. In the first year of treatment, reduction in the area under the curve and potential water repellency was observed in 75% of the samples. In the second year, such reduction was greater in all the soil samples and at \(w_{60^\circ C}\) and/or \(w_{AD}\) hydrophilic conditions were reached. \(w_{NON}\) decreased in 38% of the samples (subplot n, p, q).

For both fields, the addition of 50 and 100 t ha\(^{-1}\) of GRF had mixed results between the soil samples, therefore effects under such concentrations were not well-defined.
Figure 27. Water repellency as function of soil water content for field 3100 (OC kg kg$^{-1}$). Effect of GFR concentrations: 0 (a-c), 50 (d-f), 100 (g-i), 300 (j-l), and 500 t ha$^{-1}$ (m-o). Pretreatment: 3100_1, first year: 3100_2.
Figure 28. Water repellency as a function of soil water content for field 1300 (OC kg kg$^{-1}$). Effect of GRF concentrations: 0 (a-d), 50 (e-h), 100 (i-l), 300 (m-p), and 500 t ha$^{-1}$ (q-t). Pretreatment: 1300_1, first year: 1300_4, second year 1300_5.
4.2.2 Water repellency parameters and soil properties

The differences between pretreatment (3100_2, 1300_4, 1300_5) and treatment (1300_1, 3100_1) on OC and functional SWR parameters of south Greenlandic soils is shown in Figure 29. Due to the small sample sizes, only results with low standard deviation were considered.

For field 3100 (subplots a-e), SWR\textsubscript{AREA} and $w_{\text{NON}}$ exhibited a greater reduction with the application of 300 and 500 t ha\textsuperscript{-1} related to the control. WR\textsubscript{AD} and WR\textsubscript{60°C} decreased with the application of 500 t ha\textsuperscript{-1}, and OC did not show any reduction under the treatment.

On the other hand, for field 1300 in the first year of treatment (subplots f-j), OC, SWR\textsubscript{AREA} and $w_{\text{NON}}$ presented lower values under 500 t ha\textsuperscript{-1} of GRF related to the control. WR\textsubscript{AD} and WR\textsubscript{60°C} decreased under all GRF concentrations. In the second year, such effects enhanced except for $w_{\text{NON}}$. Under 100 t ha\textsuperscript{-1} WR\textsubscript{AD} and WR\textsubscript{60°C} were not reduced in the second year neither.

When looking at Figure 29, it is clear that a correlation exists with the use of GRF as soil amendment, i.e., functional SWR parameters and OC decreased with growing GRF concentrations, except OC in field 3100. However, taking a closer look at values when exposed to 100 t ha\textsuperscript{-1}, the effect of the amendment is uneven for field 1300 in the two years of treatment. The standard deviation (SD) is very large, making it hard to draw specific conclusion for this treatment concentration. Nevertheless, WR\textsubscript{AD} and WR\textsubscript{60°C} exhibited a clearer, but irregular effect of all GRF concentrations for both fields. Further, due the small units used in the y axes for OC, SWR\textsubscript{AREA} and $w_{\text{NON}}$ is difficult to assume that the effect of GRF on these parameters is significative.

In addition, 50 and 300 t ha\textsuperscript{-1} had a clear effect on WR\textsubscript{AD} and WR\textsubscript{60°C} for field 3100 in comparison with the control (subplot d, e). It is, however, a very tentative conclusion due to the small sample size and large SD. A larger sample size would potentially alleviate this irregular behavior. For further studies a recommendation is made to increase the sample size to contribute to validating this tentative conclusion.
Figure 29. Effect of GRF concentrations on OC and functional SWR parameters. Subplots show the difference between the treatment and pretreatment values: field 3100_2 (a-e), field 1300_2 (g-j), field 1300_5 (i-o).
Figure 29 (subplot d, e, i, j), Figure 27 (subplot a-c), and Figure 28 (subplot a-d) the potential water repellency in dry soils were enhanced in the control plots for both fields throughout the period of the treatment. As result of the Wilcoxon signed-rank test, under normal conditions (0 t ha⁻¹) for both fields (n=7) the mean WR₆₀°C and WRₐₐ in the first year of treatment were significantly different (p=0.018) from the mean pretreatment values in the control plots. WR₆₀°C raised 11.66 mN m⁻¹ and 14.07 mN m⁻¹ in WRₐₐ, i.e., the potential water repellency increased from sightly to severe water repellent in the untreated control between sampling years. The rest of SWR parameters and OC content did not show significant changes (p>0.05).

As a result of the Kruskal-Wallis rank-sum test to compare the effect of GRF concentrations on SWR, at less than 5% significance level we found that the application of GRF, as a soil amendment in fact reduced potential hydrophobicity in south Greenlandic soils, in air dried (p<0.01) and oven dried at 60°C (p<0.001). A post-hoc analysis revealed that the mean reduction in the severity of water repellency was significantly higher at 50, 300, and 500 t ha⁻¹ of GRF relative to the control (0 t ha⁻¹) (p<0.05, Bonferroni-adjusted) (Figure 30).

The interactions between OC quality and clay control the SWR-w curve in shape and magnitude (de Jonge et al., 2009; Knadel et al., 2016; Regalado et al., 2008). Small additions of clay (< 3%) have been reported to decrease water repellency in sandy soils. This depends on the clay mineral type, not just its total amount (McKissock et al., 2002). In that sense kaolinite clays have been demonstrated to be more effective than montmorillonite and smectite in reducing water repellency in sandy Australian soils (McKissock et al., 2000).

The cation exchange capacity (CEC) of the GRF used in this study has been reported to be comparable with kaolinitic-clay dominated soils. Further, the specific surface charge of GRF is higher than kaolinitic-clay soils (Pesch et al., 2022). Therefore, GRF has the capacity to cover hydrophobic organic compounds in water repellent soils from the south of Greenland.

The addition of kaolinite to reduce water repellency in sandy soils was performed by Leelamanie & Karube, (2010b). The addition of 1-2% of kaolinite in air dry and oven dry soils at 30°C, from 0.03 to 0.08 kg kg⁻¹ of soil moisture. It resulted in a decrease of water repellency up to hydrophilic behavior. This explains the complete decrease of WR₆₀°C and WRₐₐ in south
Greenlandic soils, even with the natural increased between sampling years in untreated control.

The reduction in SWR_{AREA}, w_{NON}, and OC in Figure 29 and Figure 30 that was observed with increasing GRF concentrations was not statistically significant. Nevertheless, GRF has potential to alleviate water repellency in south Greenlandic soils, which could be reflected in a longer time treatment. Further research is recommended to corroborate these findings.
Figure 30. Box plot representation of the effect of GRF concentrations on OC and functional SWR parameters after the first year of treatment. Fields 1300_4 & 3100_2 were combined (n=7). a) total degree of soil water repellency (SWR\textsubscript{AREA}), b) critical soil-water content (w\textsubscript{NON}), c) soil water repellency after dried at 60°C (WR\textsubscript{60°C}), and d) soil water repellency after air dried (WR\textsubscript{AD}), e) organic carbon (OC). Note that surface tension of water (71.27 mN m\textsuperscript{-1}) was subtracted from c and d to reverse the relationship. Asterisks (*) denote significant differences between treatment concentrations and control (0 t ha\textsuperscript{-1}) from Wilcoxon rank-sum (p<0.05 Bonferroni-adjusted)
As mentioned before OC was the main control of the degree of water repellency for south Greenlandic soils. Field 3100 was positively correlated with OC, and it explained the 84% and 80% variation of SWR\textit{AREA} and \textit{wNON} respectively. In the same way, 66% of WR\textsubscript{60°C} and 53% of WR\textsubscript{60} were explained by OC content.

Such relationships were observed in the control plots for SWR-w curves in both fields. Nevertheless, with the addition of different GRF concentrations the role of OC on SWR changed; SWR parameters were less extended than the pretreatment, even with increasing OC values, especially with the addition of 300 and 500 t ha\textsuperscript{-1} (see subplots h, m, n in Figure 27 and o, p, q in Figure 28). Similarly, in Figure 29, the OC in field 1300 decreased with increasing GRF concentration and SWR parameters followed partially the OC trend. On the other hand, OC in field 3100 did not show any notable change over the treatment, and SWR parameters did not followed OC behavior.

Figure 5 in Appendix 1 (Webber; et al., 2022) shows the scatter plot of SWR\textit{AREA}, \textit{wNON} and WR\textsubscript{60} as functions of OC for Upernaviararuk (field 1300) and South Igaliku (field 3100) and how soil samples under 50, 100, 300 and 500 t ha\textsuperscript{-1} GRF concentration behaved in relation with OC compared with the pretreatment. The main change was observed on WR\textsubscript{60}, where the soil samples were located an increasing distance of the regression line along with increasing GRF concentrations, i.e., the potential to develop water repellency in dry soils lessened with the addition of higher GRF concentrations, independent of OC content. Therefore, the control of OC on SWR was diminished.

The same phenomena were observed for WR\textsubscript{AD} (figure not plotted) and WR\textsubscript{105°C}; hence having the same result, in some proportion in SWR\textit{AREA}. There was no clear effect of GRF on \textit{wNON} for the treatment. Since kaolinite has shown and increased in the critical soil-water content when this type of clay has been used to alleviate water repellency. Thus, this could explain the variation of \textit{wNON} in this study (Leelamanie & Karube, 2010b).

\textbf{4.2.3 Conclusion}

The use of GRF as potential soil amendment reduced water repellency in south Greenlandic soils. The addition of 300 and 500 t ha\textsuperscript{-1}, alleviated the most the total degree of water repellency in both fields. Despite of the decrease was not statistically significative, GRF shown
a potential to reduce SWR. It can be reflected in a longer time treatment. Therefore, further research is necessary to corroborate these findings.

The main effect of GRF amendment was observed in potential water repellency, WR_{50\degree C} and WR_{AD}, where the degree decreased up to shift the hydrophobic soil to no water-repellent. Considering that climate change will enhance with longer dry periods in the Arctic region, the use of GRF as a natural soil amendment could diminished negative effects in yield production.

### 4.3 Normalization of SWR_{AREA} to soil water retention

The results of this section represent a brief overview of the findings described in the paper by Weber et al. (2022), which is attached in the appendix section.

As mentioned before in section 4.2, due the small units used in the y axes in Figure 29 for SWR_{AREA} and w_{NON} it was difficult to assume that the effect of GRF concentrations on these parameters is significative. Further, the disproportionate response of SWR parameters to OC fluctuations under the treatment, made harder to determine the impact of GRF on SWR_{AREA} and w_{NON}.

Figure 7 in Appendix 1 (Webber; et al., 2022) shown the normalization of SWR_{AREA} to the soil water retention by dividing SWR_{AREA} to the inverse negative CS-slope (-\alpha^{-1}). The letter one was obtained from the slope of the pF-W relationship for both fields (Figure 6 in Appendix 1). As result, the normalization revealed the effect of GRF concentration on SWR_{AREA} without the interaction of OC. Since the water retention in the dry end of the soil characteristic curve is controlled by adsorption of water onto the soil specific surface area, and it is related with OC, clay, and fine silt content; the effects of GRF treatment can be hidden by variabilities in fine minerals and OC of the fields. Consequently, desorption isotherms were used to normalize SWR_{AREA} and eliminate the OC and fine minerals noise.

In fact, WR_{AREA}/-\alpha^{-1} was reduced with rising GRF concentrations. It was higher for field 3100 (SI) compared with field 1300 (UP) with 500 t ha^{-1} GRF. This difference between fields can be explain by the fact that field 3100 had the lowest OC and clay values (Table 5 & Figure 20) among the fields analyzing in section 4.1. Hence, the clay that cover the organic hydrophobic compounds with GRF treatment would be less extended in field 3100 than field 1300.
5 OVERAL CONCLUSIONS

Soil water repellency is a key issue to be handled due to its negative consequences in agricultural production, especially in areas prone to long dry period. This thesis set out to measure the effect use of the GRF as soil amendment on water repellency soils. Introducing GRF into Greenlandic soils with the purpose of improving agricultural soil characteristics and hence yield production was investigated.

In this study 127 soil samples collected from four agricultural fields from Denmark and south of Greenland were analyzed. The degree of water repellency for Danish peat soils (n=25) and south Greenlandic soils (n=47) was very strong.

The functional SWR parameters: $\text{SWR}_{\text{AREA}}$, $\text{w}_{\text{NON}}$, $\text{WR}_{\text{AD}}$, and $\text{WR}_{60^\circ \text{C}}$ were higher in Danish soils, which means that they have a larger potential to develop strong hydrophobicity under dry conditions.

Organic carbon and soil moisture were determined to be the main catalyst of the degree of repellency in the Greenlandic and Danish soils. $\text{SWR}_{\text{AREA}}$ and $\text{w}_{\text{NON}}$ proved to be linearly correlated with organic carbon, which explained the 97 and 96% of the variability. $\text{WR}_{\text{AD}}$ and $\text{WR}_{60^\circ \text{C}}$ have shown a sigmoidal relationship with organic carbon. It explained the variability by 65 and 71% respectively.

GRF proved to reduce potential water repellency in dry soil from the south of Greenland. Around 75% of the soil samples reached hydrophilic conditions either at $\text{WR}_{\text{AD}}$ and/or $\text{WR}_{60^\circ \text{C}}$, with the addition of 50, 300 and 500 t ha$^{-1}$ GRF. For $\text{SWR}_{\text{AREA}}$, the normalization of SWR with the soil water retention, eliminated the interaction of OC, and shown a clearly the decrease of the total degree area of water repellency with the application of 500 t ha$^{-1}$, especially for soils with low amount of OC and clay.

The reason GRF is such a good potential soil amendment is due to its mineral composition, high cation exchange capacity, and specific surface change. GRF is furthermore characterized by containing a high degree of fine particles and being completely hydrophilic. Therefore, GRF as a natural soil amendment has considerable capacity to alleviate water repellency in agricultural soils.


Scientific paper:

Glacial rock flour reduces the hydrophobicity of Greenlandic cultivated soils

Core ideas:

- Applying fine-grained glacial rock flour may alleviate hydrophobicity of subarctic soils.
- Hydrophobicity parameters ($WR_{105}$, $WR_{60}$, $W_{NON}$, $WR_{AREA}$) were assessed in two field trials.
- Hydrophobicity was reduced at applications $\geq 300$ t/ha, particularly in the less clayey and organic field.
- Normalizing $WR_{AREA}$ to the water retention enabled comparisons between soil types.

Title: Glacial rock flour reduces the hydrophobicity of Greenlandic cultivated soils

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Abbreviations:

CS, Campbell, Shiozawa; GRF, glacial rock flour; MED, molarity of an ethanol droplet; OC, organic carbon; RH, relative humidity; SI, South Igaliku; UP, Upernaviarssuk; W, gravimetric water content; \( W_{\text{NON}} \), critical water content; WR, water repellency; \( WR_{\text{AREA}} \), total water repellency; \( WR_{60} \), water repellency after 60 °C heat pre-treatment; \( WR_{105} \), water repellency after 105 °C heat pre-treatment
Soil water repellency (WR) is prevalent across South Greenlandic cultivated fields, where it can reach extreme levels. Since WR can be a constraint to agricultural production, it would be beneficial to ameliorate WR in South Greenland. Fine-grained glacial rock flour (GRF) is available in the inner fjords of South Greenland and can potentially be used as a soil amendment. Therefore, this study aimed at testing whether application of GRF (application rates of 0, 50, 100, 300, and 500 t ha\(^{-1}\)) to soils across two cultivated field trials in South Greenland could reduce WR. The two fields (UP and SI) differed in the range of clay (UP: 0.05 – 0.11 kg kg\(^{-1}\); SI: 0.03 – 0.05 kg kg\(^{-1}\)) and organic carbon (OC) contents (UP: 0.04 – 0.13 kg kg\(^{-1}\); SI: 0.01 – 0.03 kg kg\(^{-1}\)). The degree of WR was measured across a gradient in water content (W) ranging from oven-dry to the critical water content (W\(_{\text{NON}}\)) to obtain whole WR-W curves. Application rates of \(\geq 300\) t ha\(^{-1}\) caused most WR-W curves to become temporally hydrophilic around air-dry conditions. A reduction in WR was observed at these application rates for both total WR (WR\(_{\text{AREA}}\)), W\(_{\text{NON}}\) and WR after heat pre-treatments (WR\(_{105}\) and WR\(_{60}\)). Some effects of GRF on WR were masked by texture and OC variations, and a standardization of WR\(_{\text{AREA}}\) to soil water retention (by utilization of the Campbell-Shiozawa model on water vapor sorption isotherms) revealed that GRF reduced WR\(_{\text{AREA}}\). The reduction in the normalized WR\(_{\text{AREA}}\) was highest for the SI field, which might be ascribed to this field's relatively low OC and clay contents. Thus, GRF could efficiently reduce WR across two Greenlandic field trials.
INTRODUCTION

Water repellency (WR) originates from the presence of hydrophobic organic compounds that cover the soil mineral fraction (Bisdom et al., 1993). The behavior of WR is dynamic since amphibolic compounds can reorientate and expose either hydrophobic or hydrophilic ends according to water content (W) (Doerr et al., 2000). The WR-W curve is often characterized by the total WR (trapezoidal integrated area of the WR-W curve; WR_{AREA}) and the critical W (W_{NON}) (de Jonge et al., 1999; Dekker et al., 2001; Kawamoto et al., 2007; Regalado et al., 2008), and the severity of WR after heat pre-treatments at 60 (WR_{60}) and 105 °C (WR_{105}) are also standard indices for WR characterization (de Jonge et al., 1999). Some soils are hydrophobic at water contents corresponding to pH values around or less than three (Kawamoto et al., 2007; Wijewardana et al., 2016) or even less than pH 2 (Kercheva et al., 2021). Thus, soils can be hydrophobic across relatively large ranges in W, even at water contents beyond field capacity.

The cultivated soils of South Greenland exhibit a high prevalence in soil water repellency (WR). A recent study on soils collected across 23 pasture and cultivated fields located in the three main agricultural areas in Greenland (Qassiarsuk, Igaliku, and South Igaliku) (Westergaard-Nielsen et al., 2015) revealed that 99% of these soils were water repellent with 98% of the soils being capable of reaching an extremely high degree of WR (surface tension < 40.9 mN m\(^{-1}\) (Weber et al., 2021). Water repellency can constrain agricultural production (Müller et al., 2010; Roper et al., 2015) by increasing surface erosion, reducing rain- or irrigation water infiltration, and reducing nutrient availability (Doerr et al., 2000; Roper et al., 2015). Given the high prevalence of WR in Greenland, it would be beneficial to ameliorate WR. It is possible to ameliorate WR by different methods. Among these are, i.e., cultivation, clay amendment, application of soil wetting agents, and irrigation (Wallis and Horne, 1992; Müller and Deurer, 2011). Clay amendment is often used
as an indirect amelioration technique for WR in Australia (Müller and Deurer, 2011). Further, studies have shown that clay amendment is an effective strategy for WR amelioration in both naturally hydrophobic sandy soils and "model" soils, where initially hydrophilic sands are made artificially water repellent by adding organic hydrophobic compounds (i.e., cetyl alcohol, stearic acid or organic extracts) (Ma'shum et al., 1989; Ward and Oades, 1993; McKissock et al., 2002; Diamantis et al., 2017). Clay amendment is only economically feasible if the clay is readily available from a local source (Hallet, 2008; Müller and Deurer, 2011). Pesch et al. (2021) reported that glacial fjords in South Greenland contain vast amounts of glacial rock flour (GRF); a glacially derived mineral material with high clay- and silt-sized particles that have a specific surface area corresponding to soils dominated by kaolinite clay (Pesch et al., 2021). Thus, it would be beneficial if the nearby glacial rock flour deposits could be applied to Greenlandic agricultural soils to ameliorate WR.

In general, there is wide acceptance that kaolinite is useful for WR amelioration, whereas studies have reported both successful and less successful results for illite and montmorillonite. The effectiveness of kaolinite in reducing WR as compared to montmorillonite might be attributed to the comparably high dispersibility of kaolinites, which can facilitate a readily, long-term, and even distribution of the clay mineral over hydrophobic grain surfaces (Ma'shum et al., 1989; Ward and Oades, 1993; Cann, 2000). The effect clay amendment on WR is not enabled until the soil has been through one or more wetting- and drying cycles, since wetting facilitate the distribution of clay around soil particles and drying facilitate the masking of hydrophobic compounds (Ward and Oades, 1993; McKissock et al., 2002).

Based on two field trials located in Southern Greenland, the overall aim of this paper was to assess changes in WR 1-2 years after field application of GRF in different concentrations (0, 50,
100, 300, and 500 t ha\(^{-1}\)). Assessing the effect of GRF on WR 1-2 years after application allows
the soil to undergo several wetting and drying cycles, which can provide a realistic assessment of
the efficacy of GRF for WR amelioration in Greenland. Thus, the aims of this paper were to:

- Perform a qualitative analysis of WR-W curves for two fields before (pre-GRF) and after
  GRF treatment (post-GRF)

- Assess changes in WR parameters (WR\(_{\text{AREA}}\), \(W_{\text{NON}}\), \(WR_{60}\), and \(WR_{105}\)) between post-GRF
  and pre-GRF

- Compare basic linear relations between the WR parameters and OC for pre-GRF and post-
  GRF
MATERIALS AND METHODS

Field trials

Two field trials were established in Upernaviarsuk (UP, 60°44′57.3″N 45°53′24.4″W) and South Igaliku (SI, 60°53′15.2″N 45°16′37.1″W) in 2018 and 2019, respectively (Fig. 1).

Figure 1. a) Map showing the wider location of the study area in Greenland and b) the location of the glacial rock flour (GRF) site and the experimental sites in Upernaviarsuk (UP) and South Igaliku (SI). Drone images of the UP (c) and SI (d) field trials immediately before the incorporation of the glacial rock flour (GRF). The plot extent is highlighted with grey squares, and the numbers within each plot denote the application rate of GRF in t ha⁻¹.
The UP soil was classified as a humic Cambisol with a loamy sand texture that developed on colluvium originating from granodioritic gneiss and granites of the Julianehåb batholith (Kokfelt et al., 2019) since the deglaciation approximately 10 ka BP (Bennike et al., 2002). The SI soil was classified as a brunic Arenosol with a loamy sand texture that developed on top of aeolian and fluvial sediments originating from the surrounding bedrock, including hornblende bearing diorite and gabbro and olivine bearing syenite (Kokfelt et al., 2019). Both fields have been cultivated and used for hay production with perennial grasses for > 50 years. Prior to the experiment both fields had been vegetated by similar commercial grass mixtures, which primarily consisted of timothy (Phleum pratense L.), colonial bentgrass (Agrostis tenuis L.), Kentucky bluegrass (Poa pratensis L.), Perennial ryegrass (Lolium perenne L.), and red fescue (Festuca rubra L.), and neither of the fields had been tilled within the last three years.

The UP-field trial was established first as part of a feasibility study at the agricultural research station and agricultural school in Upernaviarsuk immediately after the harvest in mid-august 2018. The trial was arranged in a randomized block design with 5 application rates of glacial rock flour, 0 (control), 50, 100, 300, and 500 t ha\(^{-1}\), which were replicated (n = 4), yielding a total of 20 field plots. Each plot was 3 × 3 m and the spacing between each plot was 3 m along with the direction tillage and 2 m perpendicular to the tillage direction. The glacial rock flour was manually disaggregated, applied evenly on the soil surface, and subsequently incorporated thoroughly into the upper 15 cm of the A horizon using a disc harrow. The field was sown with the commercial grass mixture consisting of 85 % timothy (Phleum pratense L.), 10 % colonial bentgrass (Agrostis tenuis L.), 3 % Kentucky bluegrass (Poa pratensis L.), and 2 % Dutch clover (Trifolium repens L.). Commercial NPK fertilizer (17:7:14) was applied in early spring every year, corresponding to an application rate of approximately 110 kg N ha\(^{-1}\), 45 kg P ha\(^{-1}\), and 91 kg K ha\(^{-1}\).
The SI field trial was established in 2019 almost identical to the UP trial, with the only difference being a reduced number of replications (n = 3, total plots = 15) due to the size of the field.

The GRF utilized in both experiments originated from a large (approximately 1,400,000 m³) local deposit in Ataanasit (AT, 61°00′47.8″N 45°27′04.5″W), which consists of raised marine sediments originating from the surrounding glacial outwash streams (Pesch et al., 2021). The deposit is one among many in the area that has been exposed due to isostatic rebound after the last deglaciation approximately 10 ka BP (Bennike et al., 2002). The GRF is non-saline, consisting of 0.44 kg kg⁻¹ surface-active particles (≤ 20 µm) with a mineralogical composition dominated with feldspars (73 %), quartz (15 %), and traces of amphiboles (6 %) as well as micas (6 %). A detailed physical characterization of the utilized GRF and other GRFs from southwest Greenland can be found in Pesch et al. (2021).

**Soil sampling and analyses**

Bulk soil was sampled from each plot prior to applying GRF to service as a secondary control for each plot while also establishing a baseline in soil water repellency across the two fields. The soil sampling after treatment with GRF was performed immediately after harvest in mid-August 2020 in both field trials. Thus, the GRF has been incorporated into the soil for two years in UP trial and one year in SI trial at the after-treatment sampling. During each soil sampling, approximately 2 kg of bulk soil was excavated in the A horizon immediately below the turf layer resulting in a total soil depth of approximately 5–10 cm. A 2 kg GRF sample was also acquired by mixing 12 representative subsamples from the excavated material prior to the application in the field. Before
further analyses, all bulk samples were stored at 2 °C and subsequently air-dried at 20 °C. Particle size distribution was determined by a combination of wet-sieving and the pipette method after organic matter removal (Gee and Or, 2002). Total organic carbon was measured by dry combustion with an ELTRA Helios C-Analyzer (ELTRA GmbH, Haan, NW, Germany). The organic carbon was set equal to the total organic carbon as all samples tested negative for calcium carbonates using a 10 % HCl solution.

Soil water repellency

The molarity of an ethanol droplet test (MED; de Jonge 1999; king 1981; Roy and McGill, 2002) was used to determine each soil's soil water repellency (WR). The WR was measured across a range in gravimetric water content (W) to account for the entire soil water repellency characteristic, i.e., WR-W curve (Fig. 2). The range in W was obtained by applying different pre-treatments to the soils: Two oven-drying pre-treatments were used to account for the dry range (i.e., with a W below air-dry) of the WR-W curve and serve as standardized WR indices. The two oven-drying pre-treatments consisted of oven-drying the soil at 105 °C for 24 h and measuring the WR directly after cooling in a desiccator for 2 h (WR\textsubscript{105}), and oven-drying the soil at 60 °C for 24 h followed by a 48 h equilibration at 20 °C in a climate-controlled laboratory (WR\textsubscript{60}). Further, WR was measured on a series of rewetted soil samples where the W ranged between air-dry and the critical water content (W\textsubscript{NON}) for each soil (Fig. 2). The rewetted soil samples were made by mixing 20 g of air-dry soil with tap water in Ziploc bags and equilibrating the samples in a 4 °C dark room for 3 weeks. The desired W for each series was calculated based on the expected W\textsubscript{NON}, which was calculated using the OC-based PTF for W\textsubscript{NON} created by Weber et al. (2021) for 145 Greenlandic agricultural topsoils.
Figure 2. Conceptual figure showing the water repellency (WR) as a function of gravimetric water content (W), and the four parameters derived from the WR-W cure. The WR after oven-drying at 105 °C and 60 °C is denoted WR$_{105}$ and WR$_{60}$, respectively, and WR$_{AREA}$ is the trapezoidal integrated area of the WR-W curve. The W above which the soil sample is hydrophilic is denoted W$_{NON}$.

The MED measurement was performed using dilution series of ethanol and deionized water with ethanol concentrations ranging between 0.00 and 0.80 m$^3$ m$^{-3}$ in 0.01 m$^3$ m$^{-3}$ increments. First, pretreated soil samples were quickly placed in small plastic cups, and the soil surface was smoothed and leveled with a knife. Thereafter, the samples were immediately subjected to a normal stress of 60.9 Nm$^{-2}$ for two minutes using a tight-fitting press that minimized water evaporation prior to the MED measurement. Droplets of 60 μL ethanol solution were left on the soil surface to infiltrate, and the WR, i.e., surface tension (mN m$^{-1}$), of the soil sample was derived from the highest ethanol concentration that did not infiltrate within five seconds as outlined by Roy and
McGill (2002). The actual W at each WR measurement was obtained by oven-drying a subsample of the pretreated soil at 105 °C for 24 h. The total degree of WR for each soil was calculated using the trapezoidal integrated area under the WR-W curve (WRAREA). A conceptual figure of a typical WR-W curve and the derived WR parameters is shown in Fig. 2.

Measurement of water vapor sorption

Water vapor sorption isotherms at 25 °C were measured on all air-dry samples using an automated vapor sorption analyzer (METER Group Inc., Pullman, WA, USA). A full adsorption/desorption loop was measured in the relative humidity (RH) range of 3–93 % with a resolution of 2 % RH, and the endpoint W was subsequently measured by oven-drying at 105 °C for 24 h. An in-depth description and discussion of the procedure can be found in Arthur et al. (2014).

The water sorption isotherms were subsequently converted to pF-based soil water retention curves (pF-W relationship) using the Kelvin equation (Eq. 1) and the Schofield equation (Eq. 2):

\[ \psi = \frac{RT \ln(RH)}{M_{H_2O} g} \]  

(1)

\[ pF = \log_{10}(|\psi|) \]  

(2)

where \( \psi \) is the soil water matric potential (cm H2O), R is the ideal gas constant (8.31 J mol\(^{-1}\) K\(^{-1}\)), T is the temperature (Kelvin), \( M_{H_2O} \) is the molecular mass of H2O (0.018 kg mol\(^{-1}\)), g is the gravitational acceleration constant (9.807 m s\(^{2}\)), and RH is the relative humidity (%).
Normalization of the SWR\textsubscript{AREA} to the soil water retention

The simple semi-logarithmic Campbell-Shiozawa (CS) model (Campbell and Shiozawa, 1992) was utilized as a soil water retention model to normalize the measured SWR\textsubscript{AREA} to the soil water retention and thereby enable direct comparison across the treatments and field trials.

To avoid hysteretic effects on the water vapor sorption, the CS-model (Eq. 3) was fitted to the desorption isotherm between pF 6.35 and 5.69, corresponding to a RH between 20 and 70 %:

\[ pF = pF_0 + \alpha W \]  

(3)

Where \( pF_0 \) is the pF at zero water content, \( W \) is the gravimetric water content (kg kg\(^{-1}\)) and \( \alpha \) is the dimensionless slope of the pF-W relationship.

The normalization was performed by dividing the SWR\textsubscript{AREA} to the inverse of the negative CS-slope (-\( \alpha ^{-1} \)).

Statistical analysis

The differences between post-treatment groups were evaluated with a one-way ANOVA coupled with a pairwise multiple comparison using the Holm-Sidak method (Holm, 1979). Differences between the pre-sampling and post-treatment results were analyzed for each application rate using a paired t-test. The variables were evaluated for normality and equality of group variance using the Shapiro-Wilk test and Brown-Forsythe test, respectively (Brown and Forsythe, 1974; Shapiro and Wilk, 1965). All statistical analyses were performed in Sigma Plot 14.5 (Systat Software, Inc., Chicago, IL, USA). Linear correlations between WR parameters and OC were evaluated using the coefficient of determination (R\(^2\)).
Particle size distribution and organic carbon

All SI plots and 18 of the UP plots were classified as loamy sand, while two UP plots were classified as sand and sandy loam according to Soil Survey Staff (1999). However, marked differences in the particle size distribution were apparent between the two fields despite their comparable textural classes (Table 1), with the SI field consisting predominately of fine sand (0.407–0.655 kg kg\(^{-1}\)) and the UP field exhibiting a high content of coarse sand (0.263–0.430 kg kg\(^{-1}\)). Additionally, the clay content was approximately twice as high in the UP field (0.047–0.111 kg kg\(^{-1}\)) compared to the SI field (0.026–0.050 kg kg\(^{-1}\)).
Table 1. Summary of the physical properties for the soils from the two field trials, Upernaviarsuk (UP) and South Igaliku (SI) and the glacial rock flour (GRF), prior to the GRF application: organic carbon (OC), clay (< 2 µm), fine silt (2–20 µm), coarse silt (20–60 µm), fine sand (60–200 µm), coarse sand (0.2–2 mm), the integrated trapezoidal area of the WR-W curve (WR\_AREA), the critical water content (W\_NON), the soil water repellency after 105 °C and 60°C pre-treatments (WR\_105 and WR\_60), and the inverse of the pF-W slope (-α\(^{-1}\)).

<table>
<thead>
<tr>
<th>Field</th>
<th>n Stat.</th>
<th>Clay</th>
<th>Fine silt</th>
<th>Coarse silt</th>
<th>Fine sand</th>
<th>Coarse sand</th>
<th>OC</th>
<th>WR_AREA</th>
<th>W_NON</th>
<th>WR_105</th>
<th>WR_60</th>
<th>-α(^{-1})</th>
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</thead>
<tbody>
<tr>
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<td>0.077</td>
<td>0.162</td>
<td>0.250</td>
<td>0.430</td>
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<td>8.13</td>
<td>0.307</td>
<td>44.36</td>
<td>58.93</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.047</td>
<td>0.063</td>
<td>0.129</td>
<td>0.155</td>
<td>0.263</td>
<td>0.042</td>
<td>4.65</td>
<td>0.178</td>
<td>41.54</td>
<td>51.82</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>Max</td>
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<td>0.095</td>
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<td>0.381</td>
<td>0.553</td>
<td>0.125</td>
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<td>0.488</td>
<td>48.24</td>
<td>71.27</td>
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</tr>
<tr>
<td></td>
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<td>0.008</td>
<td>0.023</td>
<td>0.054</td>
<td>0.073</td>
<td>0.022</td>
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<td>0.080</td>
<td>1.69</td>
<td>5.45</td>
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<td>0.083</td>
<td>0.012</td>
<td>0.88</td>
<td>0.046</td>
<td>48.24</td>
<td>47.21</td>
<td>0.006</td>
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<td></td>
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<td>0.078</td>
<td>0.228</td>
<td>0.655</td>
<td>0.275</td>
<td>0.028</td>
<td>3.30</td>
<td>0.121</td>
<td>71.27</td>
<td>71.27</td>
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<td>0.014</td>
<td>0.019</td>
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<td>0.049</td>
<td>0.006</td>
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<td>0.024</td>
<td>5.68</td>
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<td>0.204</td>
<td>0.202</td>
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<td>-</td>
<td>71.27</td>
<td>71.27</td>
<td>0.012</td>
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Figure 3. Water Repellency as a function of gravimetric water content (W) for the UP field (aa-at) and the SI field (ba-bo). Black curves with open white circles denote the results from the pre-sampling (P) before application of glacial rock flour (GRF), and the red lines with red open triangles denote the result after treatment with GRF (A). Each row represents an application rate of GRF, and the rows are arranged according to their OC content (brackets) at pre-sampling.
Effect of GRF on WR-W curves and WR severity

The WR-W curves of both the UP and SI fields were characterized by bimodal curve shapes (Fig. 3), with the local minimum in WR located around water contents corresponding to air-dry conditions. When comparing the WR-W curves of the pre-GRF with the post-GRF control samples (0 t ha\(^{-1}\)), the curves looked similar with small deviations. As an example, the SWR-W curve in Fig 3aa obtained a higher W\(_{NON}\) for pre-GRF, and the SWR-W curve in Fig. 3bc obtained a higher W\(_{NON}\) for the post-GRF treatment sample.

At application rates of 50 and 100 t ha\(^{-1}\), the effect of GRF was not clear from the visual comparison of the WR-W curves. However, at application rates of 300 and 500 t ha\(^{-1}\), it was possible to visually interpret some WR changes after GRF application. The samples became hydrophilic under air-dry conditions at an application rate of 300 t ha\(^{-1}\) (except for one sample from SI field). The same trend was valid for the application rate of 500 t ha\(^{-1}\), where the samples became hydrophilic at air-dry conditions (except for one sample from UP field). Thus, WR disappeared for six out of seven samples at air-dry conditions after GRF application of 300 and 500 t ha\(^{-1}\), respectively. For the WR\(_{60}\) measurement, all samples from the SI field became hydrophilic at the 500 t ha\(^{-1}\) application rate. By visual interpretation of the area underneath the curves at GRF application rates of 300 and 500 t ha\(^{-1}\), it was also possible to see that WR\(_{AREA}\) decreased for some field plots (for example, Fig. 3ap, 3aq, and 3bn).
Figure 4. Bar charts of WR\textsubscript{AREA} (a), WR\textsubscript{NON} (b), WR\textsubscript{105} (c), and WR\textsubscript{60} (d) for each application rate of GRF in Upernaviarusk (UP) field, and the same parameters in the South Igaliku (SI) field (e-h). The white bars represent the value from the pre-sampling (without GRF) and the red bars represent the values post-treatment. Capital letters denote significant groupings in the post-treatment results from the ANOVA and Holm-Sidak test ($\alpha \leq .05$), and asterisks denote significant differences between pre-sampling and post-treatment from the paired t-test (*$p<0.05$, **$p<0.01$, ***$p<0.001$). Note that WR\textsubscript{105} and WR\textsubscript{60} are presented as 71.27-WR.
(mN m⁻¹), which represent the decrease in surface tension compared to pure H₂O, in order to increase legibility.

For the UP field, the WR_AREA and W_NON on post-GRF samples were lower than the measurements for the pre-GRF samples for all concentrations of GRF (0, 50, 100, 300, and 500 t ha⁻¹) (Fig. 4a&amp;b). For the SI field, WR_AREA and W_NON of the post-GRF control samples (0 t ha⁻¹) reached a higher level than the pre-GRF samples at the same application rate (Fig. 4e&amp;f). For both fields, the WR_AREA and W_NON was consistently reduced for the post-GRF sampling campaign at 300 and 500 t ha⁻¹. Despite the clear tendencies, the ANOVA found no significant differences (p &lt; 0.05) in WR_AREA and W_NON across the post-treatment levels, and the paired t-test found no significant differences between the pre- and post-treatment values at each treatment level. However, the lack of statistical significance could in part be a result of relatively high variations in OC observed at both the field and plot level (see brackets in Fig. 3).

For the WR₆₀ and WR₁₀₅ measurements, the trends between the WR levels obtained during the pre-GRF and post-GRF sampling campaigns were not clear for GRF application rates of 0, 50, and 100 t ha⁻¹ (Fig. 4c-d & g-h). However, WR₆₀ and WR₁₀₅ were markedly lower during the post-GRF campaign than the pre-GRF campaign for the UP field at application rates of 300 and 500 t ha⁻¹. The paired t-test showed a significant (p &lt; 0.05) reduction in WR₁₀₅ between pre- and post-treatment for the highest application rate in both fields. Further, the ANOVA and Holm-Sidak test showed a significant difference in WR₁₀₅ between post-treatment levels with the 500 t ha⁻¹ being significantly (p &lt; 0.05) different to the control (0 t ha⁻¹).

The WR₆₀ was significantly lower during the post-GRF campaign than the pre-GRF campaign for the UP field at application rates of 300 and 500 t ha⁻¹. Although not significant, the
measurements after application of 500 t ha\(^{-1}\) GRF showed that the soils became hydrophilic after this GRF-treatment.

Different application rates of clay have been tested for WR remediation throughout the literature. For example, Cann (2000) applied clay in rates of 0, 50, 100, and 150 t ha\(^{-1}\) across an experimental site in Australia and obtained the highest reduction in WR for the application rate of 150 t ha\(^{-1}\). Further, Diamantis et al. (2017) applied kaolinite clayey soil onto water repellent sandy soil under olive trees at a rate of 10 t ha\(^{-1}\) in both dry and wet form, and the wet application of clay immediately reduced water repellency by 74 %. Lastly, the study of McKissock et al. (2002) applied kaolinite and smectite clay in rates between 0, 0.2, 0.4, 0.8, and 1.6 % by weight, respectively. In that study, they found a logarithmic relationship between the severity of WR and the amount of clay added to the soil.
Figure 5. Scatter plots $W_{\text{AREA}}$ (a), $W_{\text{NON}}$ (b), $W_{\text{105}}$ (c), and $W_{\text{60}}$ (d) as a function of organic carbon content (OC) for the Upernaviarsuk (UP) field, and the same parameters for the South Igaliku (SI) field (e-h). The black crosses and their best linear relationship represent the baseline of the fields before the application of glacial rock flour (GRF). The
post-treatment results are depicted with white, light grey, medium grey, and dark grey circles for application rates of 0, 50, 100, and 300 t ha\(^{-1}\), respectively, and black squares represent 500 t ha\(^{-1}\).

**Effect of GRF the WR vs. OC relationship**

For both the UP and SI fields, WR\(_{\text{AREA}}\) (R\(^2\) = .87 and .62, respectively) and W\(_{\text{NON}}\) (R\(^2\) = .62 and .73, respectively) correlated significantly and linearly to OC content for the pre-GRF sampling (Figure 5a and e). The linear relationships were stronger for the UP field, possibly due to the comparably wider range in OC content. The WR\(_{105}\) and WR\(_{60}\) from the pre-GRF sampling also exhibited significant and linear correlations to OC content (Fig. 5c, d, g, and h), although the relationship was weak for WR\(_{60}\) of the SI field, due to some samples being hydrophilic at WR\(_{60}\).

The WR\(_{\text{AREA}}\) measurements of the UP control samples were distributed around the regression line, indicating that the relation between WR\(_{\text{AREA}}\) and OC was comparable to that of the pre-GRF sampling campaign. In comparison, most GRF-treated samples were located below the regression line for WR\(_{\text{AREA}}\) (Fig. 5a). Further, the WR\(_{\text{AREA}}\) measurements of the SI control samples were located above the regression line (Fig. 5e), while the WR\(_{\text{AREA}}\) of GRF-treated samples were located below the regression line. Further, measurements of WR\(_{\text{AREA}}\) of the SI field were generally located at an increasing distance from the regression line with increasing amounts of added GRF. These results clearly indicate OC becoming less potent in creating WR after GRF application.

For W\(_{\text{NON}}\) the trend was not at clear as for WR\(_{\text{AREA}}\). However, the majority of W\(_{\text{NON}}\) measurements on GRF-treated samples were located at or below the regression line for both fields (fig. 5b and f). The effect of the clay fraction on W\(_{\text{NON}}\) has been investigated in the paper of Weber et al. (2021). In that study, it was found that clay content had an increasing effect on W\(_{\text{NON}}\) on
Greenlandic soil samples (through multiple linear regression utilizing clay and OC content as predictors). Further, the study of Lichner et al. (2006) investigated clay amendment as a method for alleviating WR, and in this study, clay amendment was also found to increase $W_{NON}$ irrespective of the type of clay mineral added (illite, kaolinite, and montmorillonite). Thus, variations in texture might interfere with the relations between WR and OC, since clay content can indirectly affect $W_{NON}$ by displacing $W_{NON}$ along the x-axis (Fig. 2). This effect of texture in WR would not only affect $W_{NON}$, but it would also displace gravimetric water contents corresponding to the remaining WR measurements and thereby also $WR_{AREA}$.

The GRF-treatments also affected the correlation between $WR_{60}$ and $WR_{105}$ and OC, respectively (Fig. 5c, d, g, and h). The majority of the $WR_{105}$ and $WR_{60}$ measurements after GRF-treatment were located close to or below the regression line. For $WR_{105}$ of the UP field (fig. 5c), the three samples treated with 500 t ha$^{-1}$ GRF were less water repellent than the remaining samples when plotted against the respective OC contents. As discussed earlier, some $WR_{60}$ measurements from UP and some $WR_{60}$ and $WR_{105}$ measurements GRF-treated samples decreased WR so much that they became hydrophilic.

**Normalization of $WR_{AREA}$ to soil water retention**

Soil water retention in the relatively dry end of the soil water retention curve is governed by adsorption of water onto the soil specific surface area available from organic carbon, clay, and fine silt content (Jensen et al., 2015; Karup et al., 2017). Therefore, some of the effects from GRF on WR-W curves can be masked by variabilities in fine minerals and OC content within and between the field plots. As mentioned, differences in clay content can affect the $W_{NON}$, since clay increases the soil's water-holding capacity and the corresponding gravimetric water content at a given pF.
value. This causes a displacement of the WR measurements when plotted against the gravimetric water content; a displacement that might not happen if WR measurements were plotted against pF-values. Thus, the extent of WR-W curves, and thereby $W_{NON}$ and $WR_{AREA}$ are sensitive to variabilities in fine minerals and OC. Kawamoto et al. (2007) plotted WR-W curves as a function of volumetric water content and pF values, respectively, and the critical water content exhibited much less variability among the samples after conversion to pF, indicating that soil water retention has a normalizing effect on WR curves. Therefore, desorption isotherms were applied to normalize $SWR_{AREA}$ to soil water retention by division of the negative inverse Campbell-Shiozawa slope, -$\alpha^1$ (Campbell and Shiozawa, 1992) (Fig. 6). This procedure was inspired by the findings of Weber et al. (2021), who found that $W_{NON}$ exhibited a stronger linear relationship with -$\alpha^1$ than OC content. The desorption curves exhibited a linear relationship between soil water potential (pF) and gravimetric soil water content in the range between pF 6.35 and 5.69, and therefore this pF-range was used to derive -$\alpha^1$. 
Figure 6. Conceptual plot detailing the desorption isotherm for one pre-treatment UP soil (white circle) and one pre-treatment SI soil (grey circle), and the linear regression of the Campbell-Shiozawa slopes ($\alpha$) between 20 % and 70 % relative humidity (RH).

After normalization of $\text{WR}_{\text{AREA}}$ with $-\alpha^{-1}$, the effect of GRF on WR was more clear (Fig. 7). For the control treatment, the $\text{WR}_{\text{AREA}}/-\alpha^{-1}$ reached a higher level in WR after treatment with GRF than the pre-GRF samples for both the UP and SI fields, indicating a slight increase in WR between the sampling years. However, the application of GRF lowered the $\text{WR}_{\text{AREA}}/-\alpha^{-1}$ such that the WR level became less after GRF treatment as compared to the level of WR during pre-sampling.

As is visible from fig. 7, the relative reduction in $\text{WR}_{\text{AREA}}/-\alpha^{-1}$ is higher for the SI field as compared to the UP field at GRF application rates of 500 t ha$^{-1}$. The higher effect of GRF on $\text{WR}_{\text{AREA}}/-\alpha^{-1}$ for the SI field might be caused by differences in texture and OC between the fields. The soil across the SI field is generally lower in clay and OC contents as compared to the UP field. Thus, the GRF treatment applies a relatively higher increase in clay content for the SI field as compared to the UP field. Further, the OC content for the SI field is relatively low, which means
that less hydrophobic surfaces are to be covered by clay minerals at the SI field as compared to the UP field.

Overall, the normalization procedure looked promising as the normalized $WR_{\text{AREA}}$ values were comparable between the two fields, indicating that the approach can be used to compare WR across soils with different compositions and soil water retention.

**Figure 7.** Bar charts of $\alpha$-normalized $WR_{\text{AREA}}$ for each application rate of GRF in UP (a) and SI (b). The white bars represent the value from the pre-sampling (without GRF), and the red bars represent the values after GRF treatment. Asterisks denote significant difference between pre-sampling and post-treatment from the paired t-test (*$p<0.05$, **$p<0.01$, ***$p<0.001$).
This study investigated the effect of glacial rock flour (GRF) amendment on soil water repellency (WR) in two Greenlandic cultivated field sites. The bimodal WR versus water content (W) curves were affected by GRF treatments of 300 and 500 t ha\(^{-1}\) in the sense that most curves became temporarily hydrophilic at the local minimum in WR around W’s corresponding to air-dry conditions. Further, a consistent decrease in all the investigated WR parameters (WR\(_{AREA}\), W\(_{NON}\), WR\(_{60}\), and WR\(_{105}\)) was observed for the treatments with 300 and 500 t ha\(^{-1}\).

With regards to the relations between WR parameters and OC, the WR\(_{AREA}\) and W\(_{NON}\) from both fields exhibited relatively strong linear relations to OC. Overall, the treatments with GRF lowered the level of WR in relation to the corresponding OC content for all the investigated WR parameters, but variances in OC and texture slightly masked the trends. Thus, normalization of the WR\(_{AREA}\) by soil water retention (utilization of the Campbell-Shiozawa slope) reduced the masking effect of varying OC and texture on WR results. The GRF-treatment clearly reduced total WR, and there was especially an effect of GRF when applied in rates of 300 and 500 t ha\(^{-1}\).

Among the different GRF application rates (0, 50, 100, 300, and 500 t ha\(^{-1}\)), the treatments with 300 and 500 t ha\(^{-1}\) reduced the level of WR, thus highlighting GRF as a possible material for ameliorating WR across Greenlandic cultivated fields.
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